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INFORMAL REPORT

APPLICATIONS OF UNDERWATER PHOTOGRAMMETRY

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ABSTRACT

The reliability of a photogrammetric system is a function of the degree of constraints applied to the system. Mapping tests have been performed to investigate the relative importance of these constraints. Underwater mapping consists of five elements: (1) ground control, (2) photogrammetric equipment, (3) field techniques, (4) photogrammetric analyses, and (5) final presentation.

Ground control was provided by a 160 foot square underwater net. A photogrammetric camera was improvised by calibrating a hand-held 70mm water-corrected underwater camera, which was mounted to the wet submersible PEGASUS. Photogrammetric analyses were performed by assembling a radial line plot for a horizontal control solution and employing this horizontal control for a vertical bridge of three models. The result was an establishment of over 1200 additional horizontal points, a planimetric map of the entire area, a detailed, one inch, contoured map of the three models, and a photo-mosaic of the area.

Tests with the submersibles STAR III and ALUMINAUT have shown that contoured strip maps can be made with parallel mounted cameras. This arrangement allows for the computations of the camera height and gives some indication of the bottom attitude. This additional information along with ground coordinates at each exposure station provides sufficient data to compile a map.

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DEVELOPMENTAL SURVEYS DIVISION
OCEANOGRAPHIC SURVEYS DEPARTMENT

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Bernard C. Byrnes

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APPLICATIONS OF UNDERWATER PHOTOGRAMMETRY

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INTRODUCTION

Photogrammetry is defined as "the science or art of obtaining reliable measurements by means of photography". [ASP, 1965] Unfortunately, photogrammetry is all too often thought of in the aerial cartographic sense and not as the versatile tool it is. One need only scratch the surface to find photogrammetry used in such diversified fields as dentistry, criminology, geodetic astronomy, meteorology, haberdashery, archaeology, and finally oceanography.

Today, underwater photography is far more prevalent than underwater photogrammetry. And this is as it should be, after all, terrestrial photography is far more prevalent than terrestrial photogrammetry. But underwater photogrammetry is a tool that has had little use. Oceanographers have done little more than look upon photogrammetry as a curio and then move on to the classical methods of oceanography. And yet there is hardly an oceanographic mission conducted that does not include underwater photography. What use is made of all this photography? If, while inspecting his photography, the oceanographer wonders: what is the size of this object; what is the separation between these objects; how high is this object; or how many objects are there per given volume of water; then he had a need for photogrammetry.

Perhaps the late application of photogrammetry is in part due to the added constraining conditions imposed upon photography taken for photogrammetric analysis. These conditions can be categorized into camera constraints, attitude constraints, and position constraints. But the degree of application of these constraints will depend on the degree of reliability required. The Deep Vehicles Branch, Naval Oceanographic Office (NAVOCEANO) recently conducted an underwater photogrammetric mapping test to investigate the importance of these constraints with a calibrated 70mm underwater camera (Rebikoff-modified Shipek) mounted on the wet submersible PEGASUS.

FIELD MAPPING TESTS

A single pair of overlapping photographs taken with two cameras with a fixed base can be contoured with relative ease. The advantage of a fixed base and parallel optical axes allows the use of even the simplest parallax meters. Such compilations have been performed at NAVOCEANO since 1961 (Figure 1) [Busby, 1962].

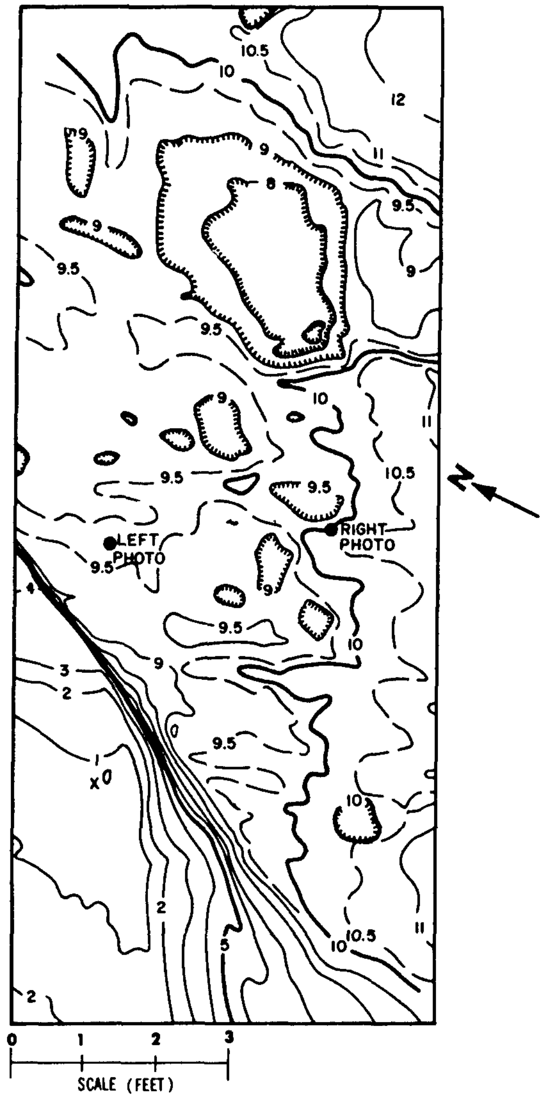
An underwater photogrammetric mapping mission, on the other hand, is perhaps the most demanding on photogrammetric technology. This challenging task was undertaken by the Deep Vehicles Branch in August 1967. Like its counterpart, aerial cartographic mapping, underwater mapping consists of five elements: (1) ground control; (2) photographic equipment; (3) field techniques; (4) photogrammetric analyses; and (5) final presentation. Also, like its aerial cartographic photogrammetry counterpart, the stereophotographic coverage is obtained with a single camera taking overlapping photographs along the flight track.

GROUND CONTROL

Ground control, points with known horizontal and vertical ground coordinates, is required if the photogrammetric solution is expected to yield dimensions, orientation, or position. And, again by definition, the completeness and reliability of the solution depends on the type, the amount, and the accuracy of the ground control. If the ground control is locally relative to some local or arbitrary coordinate system with terrestrial dimensions, then the photogrammetric solution (the map in this case) will be relative to the same local coordinate system. If the ground control is relative to some geodetic datum (sometimes called absolute control), that is, horizontal control points in coordinates of geodetic latitude and longitude and vertical control points in coordinates with respect to some level of the sea, then the photogrammetric solution will be in the geodetic system. It should be noted that relative ground control can be changed to geodetic ground control by establishing the latitude and longitude of any two points in the relative system and establishing the depth below the vertical datum of any three non-linear points in the relative system.

Basically there are two methods of obtaining ground control for a photogrammetric solution. The first method requires a ground position X, Y, and Z for each exposure station, and each time a photograph is taken the position and depth of the camera must be observed. This method may employ trilateration of position from a pair of transponders, and depth from an up-looking echo sounder [Busby, 1968]. Theoretically, only three such observations need be made, but additional positions are required to adjust the solution. Other helpful information consists of the rotational attitude of the camera (pitch, roll, and yaw) at the end of the time of exposure. The advantage of this method is the time and effort saved, since the positions of only two or three transponders are required to control areas as large as six to eight miles [Spiess, 1966]. This trilateration (transponder) system is now in the prototype stage and is under test by the Deep Vehicles Branch at NAVOCEANO (Figure 2) [Merrifield, 1968].

MOSAIC OF THE OUTCROP AS PHOTOGRAPHED BY THE CAMERA SYSTEM



MICROTOPOGRAPHIC CONTOUR MAP OF CONTOUR INTERVAL:1 DECIMETER.

FINE–GRAINED BOTTOM MAPPING

FIGURE 1

The second method is to establish at least two horizontal points (X, Y) and three non-linear vertical points (Z) within the photographed area. Again, additional points allow for an adjustment of the solution. Although these points may be natural features, they must be identifiable on the photographs.

This second method was chosen for the photogrammetric test because of its simplicity. And further, it was decided to use an independent relative network to avoid the added effort required to tie the ground control to geodetic shore stations. The horizontal network consisted of a 160 foot square with sides and diagonals marked by pre-measured wire. This configuration, the familiar quadrilateral used in terrestrial geodetic surveying, is a geometrically strong figure which can tolerate side distortions as great as 3 feet while changing the corner positions by only 0.1 foot. A site north of New Providence Island, Bahamas was selected on the following requirements: (1) quiescent and clear water; (2) generally flat bottom with occasional relief features; (3) water depth of about 35 feet; and (4) moderate water temperatures. The net was placed on the bottom by divers and held in place by five concrete clumps; one at each corner and one at the center. One diagonal was placed first, then the sides, and finally the second diagonal. The net configuration was checked by making all lines taut and observing the lines from the surface. Water clarity allowed viewing of the entire 160 foot length of line from the surface. After the visual check, divers attached additional markers at 20 foot intervals along the sides and at corresponding distances along the diagonals (Figure 3). These markers were black plastic triangles with an 18 inch base and white numbers which served not only as additional horizontal control but also as a guide to the PEGASUS pilot who flew the mission. Vertical control consisted of depth measurements with a precise pressure gage at each concrete clump.

This ground control system yielded five primary horizontal and vertical control points and thirty-two secondary control points for a study of the photogrammetric solution errors.

EQUIPMENT AND TECHNIQUES

The photographic equipment (underwater camera, intervalometer[1], stable platform, and light source) governs the specifications of flying the mission and navigation. The ratio of the principal distance[2] to the focal plane format (angle of view) governs the distance between exposures and the distance between flight lines. The camera principal distance also governs the photograph scale for a given altitude.

It was decided to conduct the photogrammetric mapping test with the wet submersible PEGASUS (Figure 4). The stability of this platform was sufficient to preclude utilization of a gimballed mount.

---

1 Some underwater cameras are equipped with an automatic timer which activates the camera at a predetermined interval. An intervalometer automatically activates the camera at the correct interval by the velocity:height ratio at each exposure station.

2 The principal distance is the perpendicular distance from the rear node to the plane of the negative. When the camera is focused at infinity and the effects of film distortion are removed, the principal distance is equal to the calibrated focal length [Lyon, 1959].

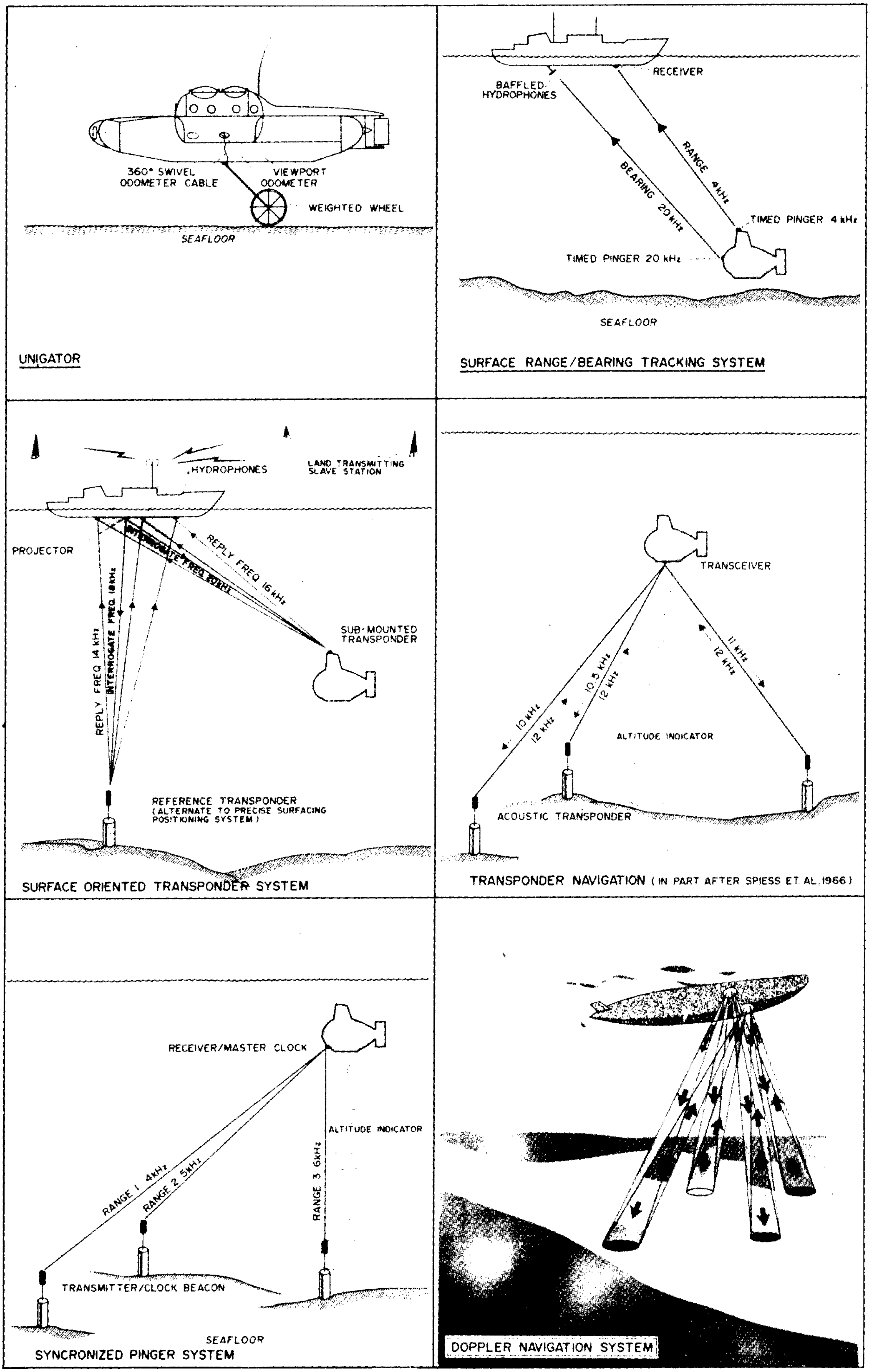


FIGURE 2 OPERATIONAL AND PROPOSED UNDERWATER NAVIGATION SYSTEMS

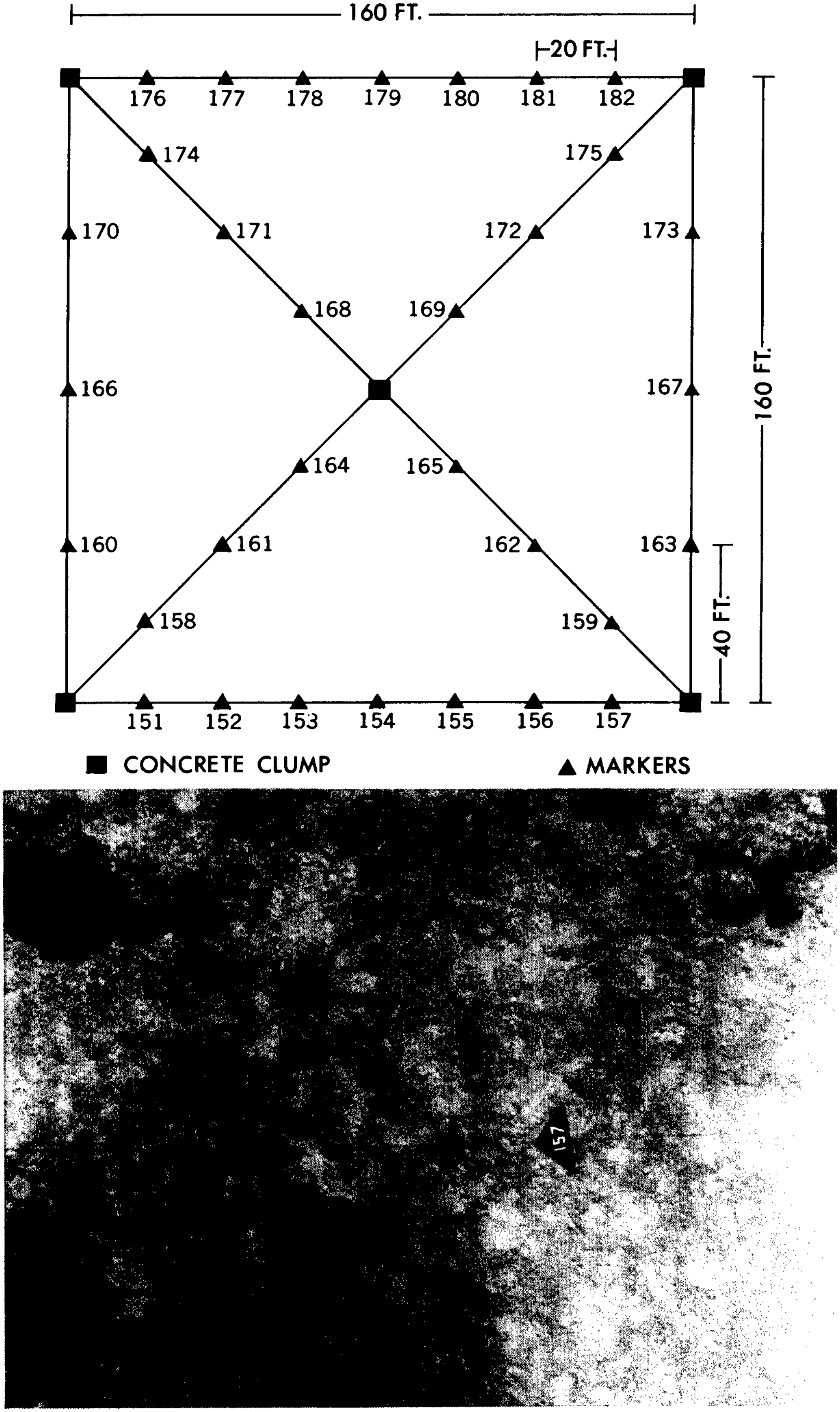


FIGURE 3 UNDERWATER CONTROL NET

FIGURE 4 FLYING THE PEGASUS

The usual stability requirements for mapping photography are: pitch, roll, and yaw[1] - less than 5 degrees; altitude variation - less than 10 percent of the altitude. Owing to the expertise of the PEGASUS pilot, the mission was conducted successfully. Since the Rebikoff-modified Shipek 70mm camera was not equipped with an intervalometer or timer, it had to be triggered by hand at the correct interval. The pilot flew at near-constant speed just under the surface and stayed on course by referring to a gyrocompass on the control module and the bottom markers. Exposure interval was maintained by the pilot who counted off the two second interval for each exposure along the track. Each flight line started and ended at a 20 foot marker. Since the flying height was 30 feet above the bottom, this yielded 20 percent side lap and the two second interval yielded 60 percent forward lap. The final plot of the flight lines indicated some wander and therefore some crowding but this resulted only in redundant photography.

PHOTOGRAMMETRIC ANALYSES

The photogrammetric solution is the reduction and interpretation of those data required to transform the photographic coordinates of various imagery into ground coordinates. This is usually a four step problem: interior orientation, relative orientation, absolute orientation, and compilation. The orientations are necessary to reconstruct, in model form, the conditions which existed at the time of photography. The compilation then transforms this model into some form of graphic presentation (i.e., a map or profile) or a matrix of model coordinates for automatic data processing.

Interior Orientation - To perform interior orientation, the camera characteristics must be known so that a mathematical or physical model of the camera can be constructed. The underwater camera becomes the first link in the photogrammetric chain.

Most photographers look upon a camera as a device for capturing a mood, an emotion, an expression, or a texture, and recording it to communicate this visual experience. The photogrammetrist on the other hand would consider a camera a tool which performs a transformation of a set of points from one coordinate system to another. The closer this transformation approaches a systematic point perspective of object space to a plane image space, the better the camera. Thus, the underwater photogrammetric camera, like any other photogrammetric camera, must systematically record images with little or no distortion which can be retrieved from a photograph plane coordinate system. But this can be achieved at no small effort.

The camera must have a high resolution, calibrated-in-water lens system with small distortion; a flat focal plane with fiducial marks or reseau (grid) marks; a film flattening device; a rapid and smooth film transport; a data chamber; and a sturdy, non-distorting construction.

The requirement for calibrating a photogrammetric lens is predicted by the requirement to reconstruct the bundle of rays that existed in object space. The calibration data usually obtained are the camera constant (calibrated focal length, principal distance or nodal image distance), lens distortion, location of the principal point (intersection of optical axis with the focal plane), fiducial coordinates or dimensions, and lens resolution.

[1]In aerial photogrammetry tilt, which is the combined effect of pitch and roll, should not exceed 6 degrees and crab (yaw) should not exceed 10 degrees [U.S. Naval Oceanographic Office, 1961].

These data can be obtained by a field test range or a bench calibrator.

Because of the vernacular problem that exists between optical physicists, photogrammetrists, and photographers - each with his own jargon for the same phenomenon - a brief discussion of lens distortion as used here is in order. Lens distortion does not refer in any way to the sharpness of the images, or image resolution, but only to the misplacement of the image position or the location of the image on the focal plane. Lens distortion therefore, is the observed position minus the theoretical position, i.e., the image anomaly. Lens distortion is comprised of a radial distortion and a tangential (prismatic) distortion. The radial distortion results from the lens design; the tangential distortion results from errors in the construction and assembly of the lens components.

Only radial distortion will be discussed here since methods are available for controlling tangential distortion by precise centering of lens elements [Amer. Society of Photogram., 1965].

A field test range calibration was conducted in a swimming pool to determine the radial distortion and camera constant (the principal distance in this case) of a Rebikoff-modified Shipek 70mm underwater camera.

The test range consisted of two stadia tapes which were fixed to the swimming pool wall and a stand which held the camera. A theodolite was used to align the camera perpendicular to the pool wall, and the distance from the forward node of the camera lens to the pool wall was measured to four significant figures (Figure 5). A number of exposures were made, each time rotating the camera approximately 45 degrees in order to average the values and to avoid systematic error. Of these, four exposures were selected at random which pictured the tapes along the format axes and diagonals (Figure 6).

Each of the four selected negatives was placed in the Mann comparator and the coordinates of each foot mark on each tape were read to the nearest micron (Figure 7).

Under the magnification of the comparator scope, it became apparent that at least three readings would be necessary to mean the random errors caused by image resolution. The best definition (resolution) which was reflected in the repeatability of the readings was found at about 8 degrees left and right of the center with the poorest definition at the edge (Figure 8). At the center, for example, the spread average was 5 microns; at 8 degrees left and right the spread average was 3 microns; while at the edge (22 1/2 degrees); the spread average was 20 microns.

Figures 9 and 10 are graphs of the photographed distance (averaged over three readings) between each foot mark on each tape and the average of both tapes. Inspection of these curves indicated a non-regularity of the left side of the tapes (0-7 feet) which persisted regardless of the attitude of the camera. Clearly the error was not due to the lens system but due to the tape itself. It was decided therefore to disregard the 0-7 foot section of the tape and use only the data from the 7-14 foot section. This provided sufficient data because, by definition, radial distortion is symetrical and a function of only the distance from the photograph center (principal point)[1]. Each photo distance was then normalized to the average 7 to 12 foot mark distance of the four negatives (Table 1).

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[1] The principal point is the intersection of the optical axis with the focal plane. The photograph center is the center of collimation. The Distance between them is made small by construction [Rebikoff, 1968].

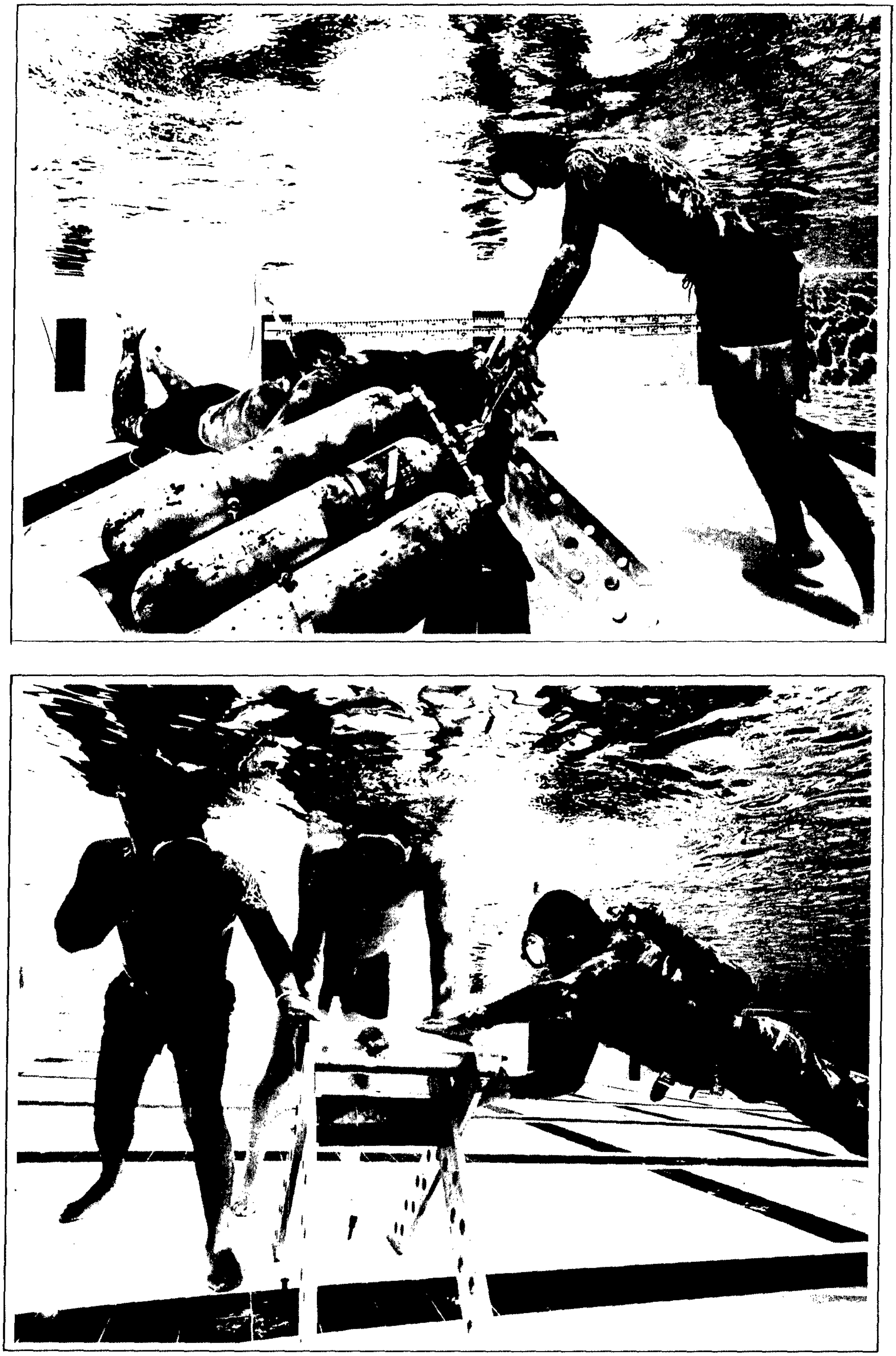


FIGURE 5 SWIMMING POOL CALIBRATION RANGE

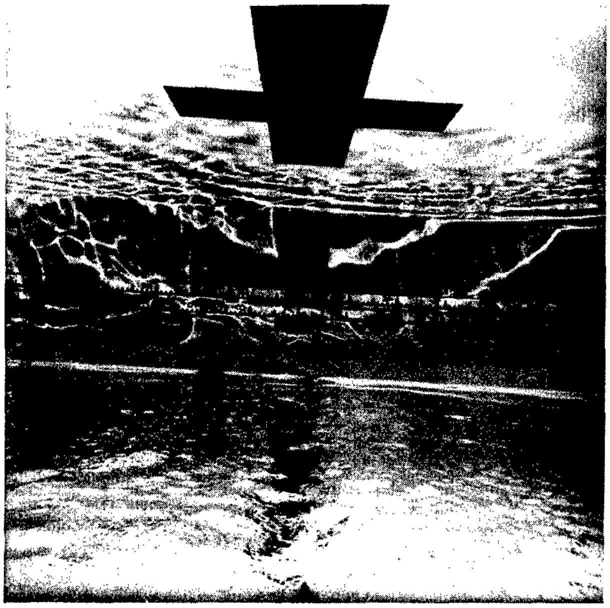


PHOTO 1

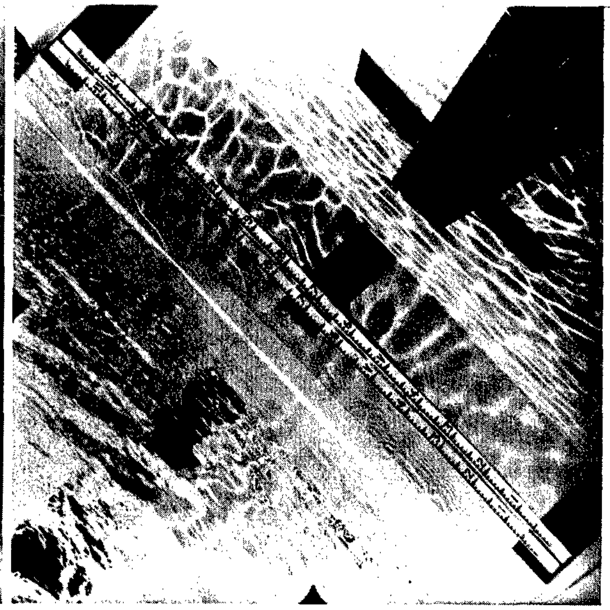


PHOTO 2

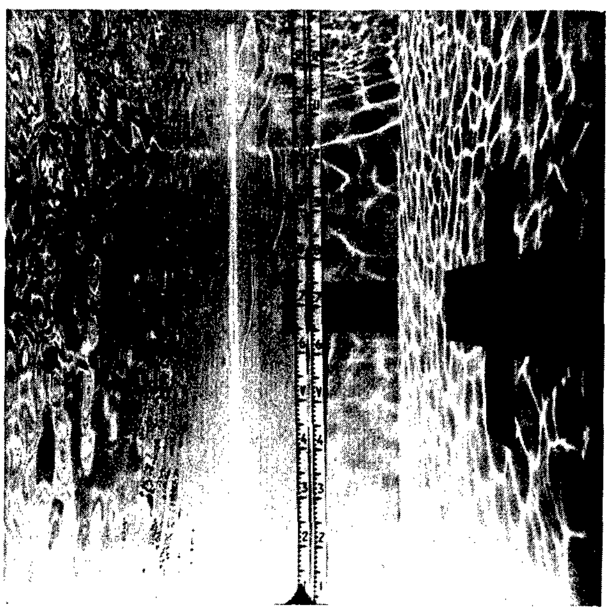
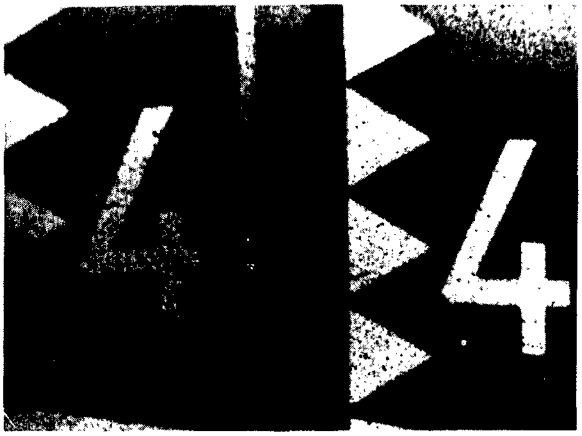


PHOTO 3

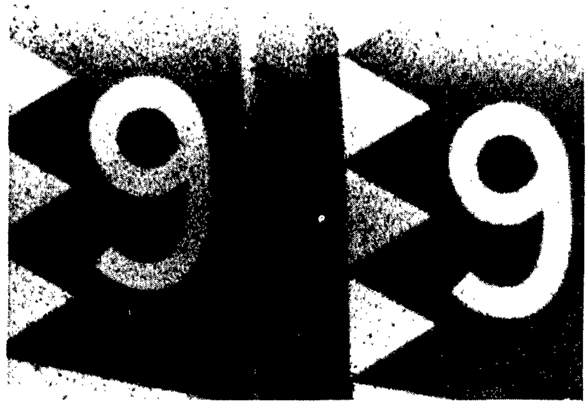
PHOTO 4

FIGURE 6 CALIBRATION TEST PHOTOGRAPHS

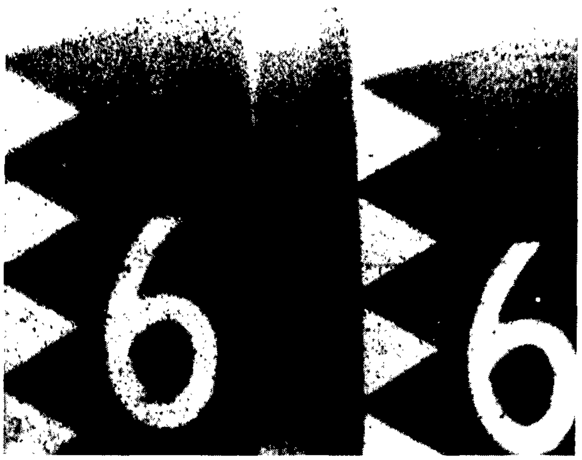
FIGURE 7 MANN COMPARITOR—DISPLAY CONSOLE AND FLEXOWRITER



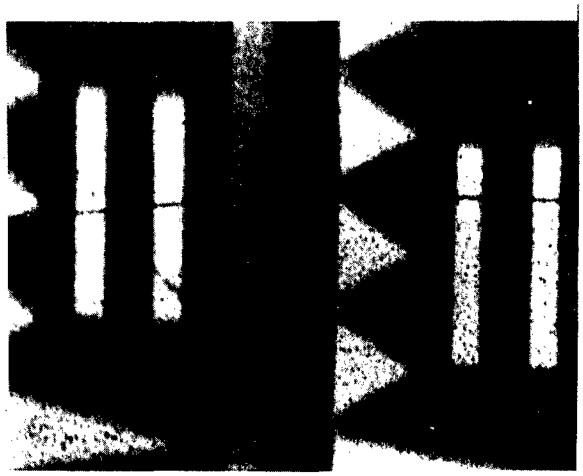
12° Left



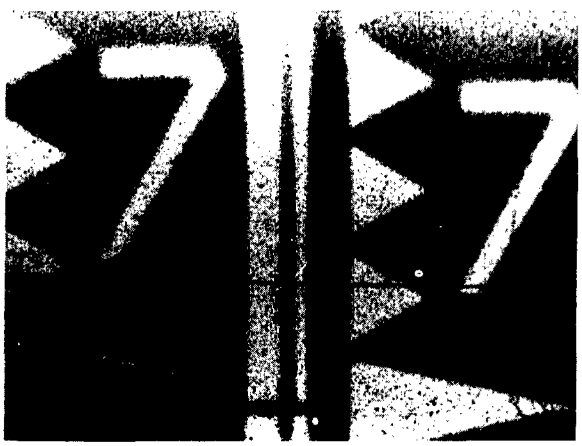
8° Right



4° Left



15 3/4° Right

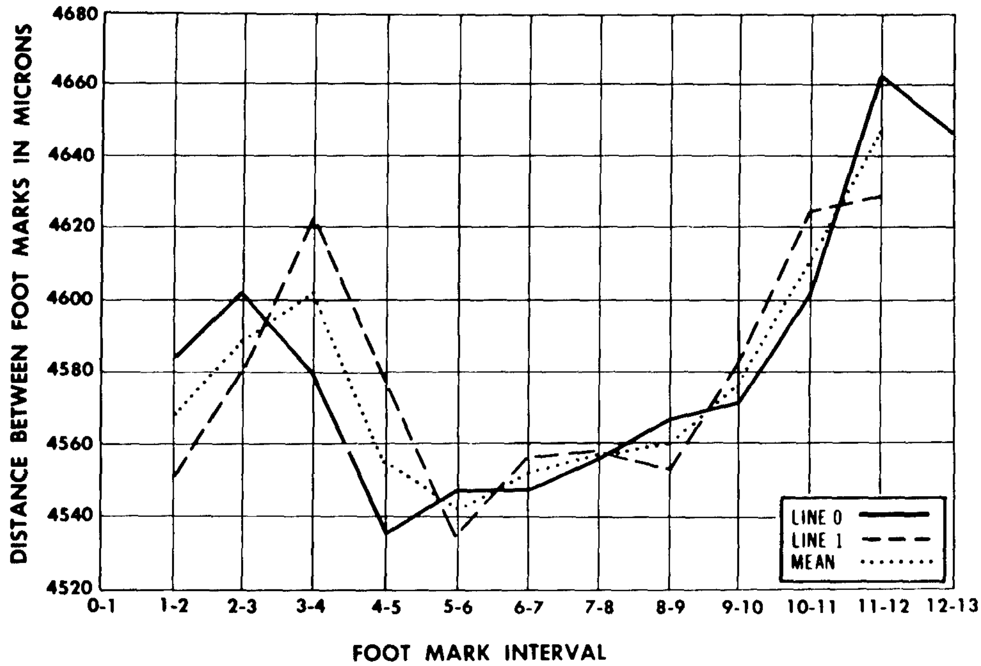


0° Center

19 1/2° Right

FIGURE 8 ENLARGED PORTIONS OF TEST PHOTOGRAPHS—APPROXIMATELY 25X

NO. 1 PHOTO DISTANCE BETWEEN FOOT MARKS



NO. 2 PHOTO DISTANCE BETWEEN FOOT MARKS

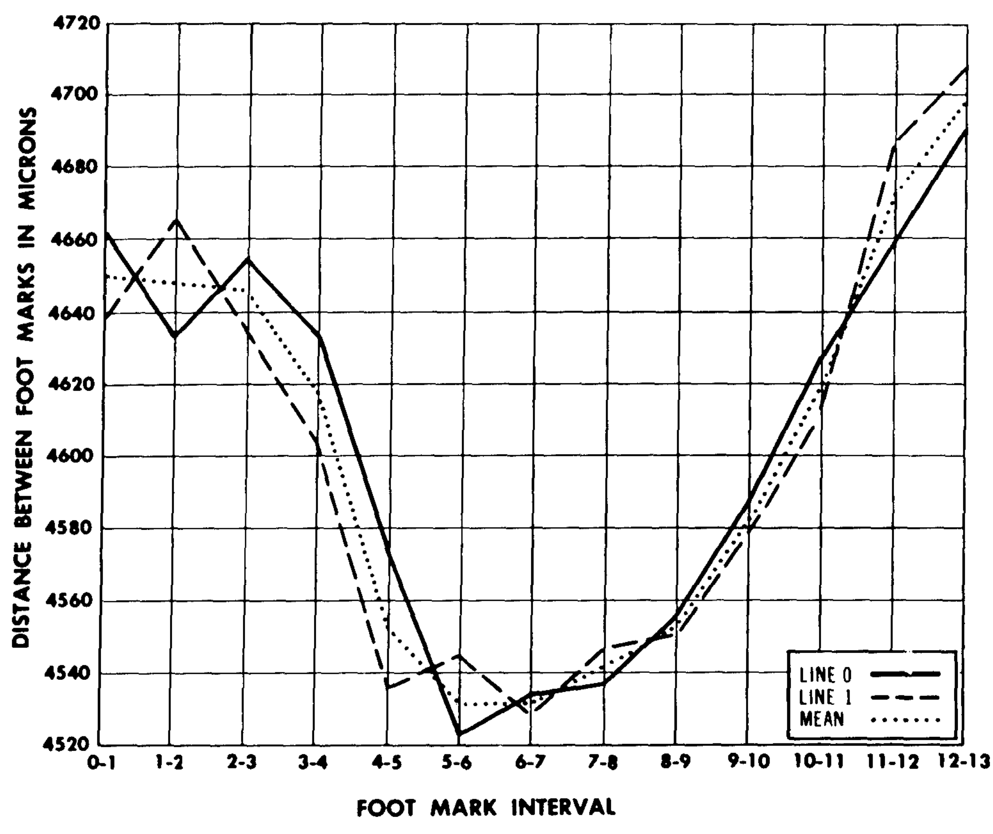
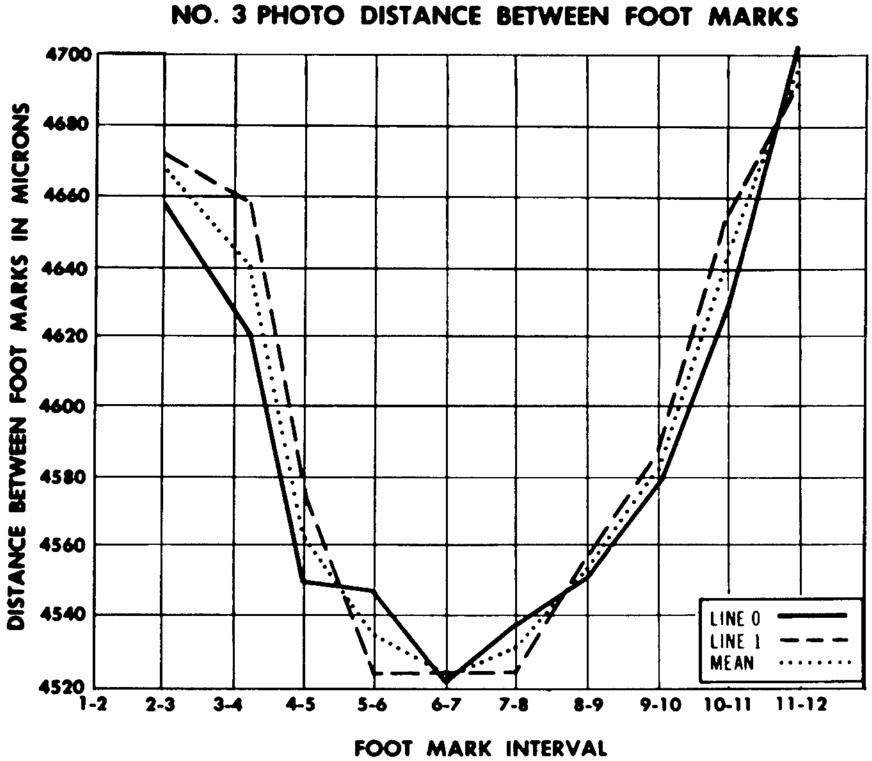


FIGURE 9


NO. 3 PHOTO DISTANCE BETWEEN FOOT MARKS
DISTANCE BETWEEN FOOT MARKS IN MICRONS
4700
4680
4660
4640
4620
4600
4580
4560
4540
4520
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
FOOT MARK INTERVAL
LINE 0
LINE 1
MEAN

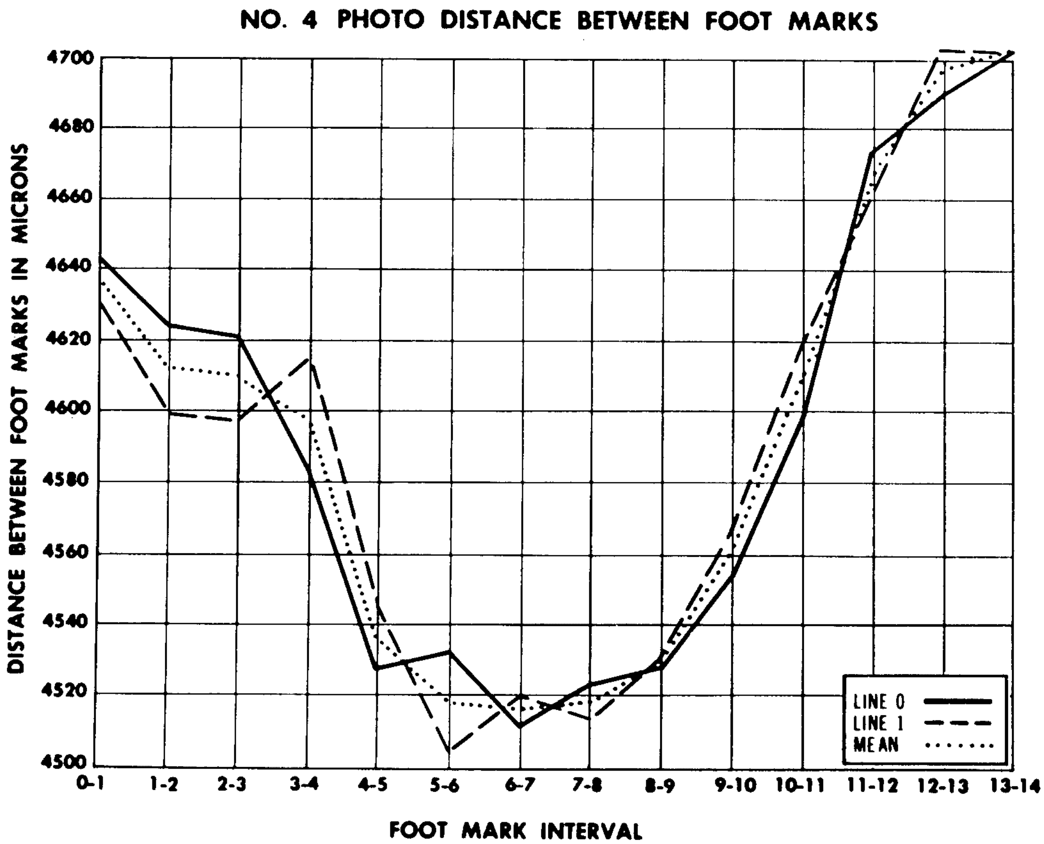

NO. 4 PHOTO DISTANCE BETWEEN FOOT MARKS
DISTANCE BETWEEN FOOT MARKS IN MICRONS
4700
4680
4660
4640
4620
4600
4580
4560
4540
4520
4500
0-1
1-2
2-3
3-4
4-5
5-6
6-7
7-8
8-9
9-10
10-11
11-12
12-13
13-14
FOOT MARK INTERVAL
LINE 0
LINE 1
MEAN

FIGURE 10

TABLE I

Photograph Normalized Mean Distance in Microns

Point	Photo 1	Photo 2	Photo 3	Photo 4	Mean
7	0	0	0	0	0
8	4556.7	4537.9	4520.3	4532.1	4537
9	9117.4	9086.9	9060.5	9072.3	9084
10	13696.1	13666.8	13634.6	13647.3	13661
11	18307.8	18283.7	18265.6	18271.9	18282
12	22953.5	22953.5	22953.5	22953.5	22954
13	27604.2	27649.3	27664.3	27667.2	27646

\- - - - -

A principal distance could be computed from each of the photograph dimensions in Table 1 and the known range dimensions (Figure 11). But the principal distance would vary depending on the photograph dimension selected for computation. In Figure 11, each photograph dimension 7 to 9, 7 to 11, 7 to 13, yields a different principal distance PD3, PD2, and PD1. The selection of any one of these principal distances would result in a distortion curve relative to the principal distance selected.

Suppose the photograph distance 7-13 is selected as the undistorted dimension - yielding PD1, then points 9 and 11 have negative distortion. If distance 7-11 is selected as the undistorted dimension yielding PD3, then points 11 and 13 have positive distortion. When one of these principal distances is finally selected, it is then designated the "calibrated" principal distance.

However, the final selection of a calibrated principal distance is based on a criterion such as equal maximum positive and maximum negative distortion, zero distortion at a certain radial distance, or a distortion curve that conforms to a particular function.

In this case, principal distance was selected on the criterion that the maximum positive distortion was equal to the maximum negative distortion. This condition was found when the photograph distance 7 to 12 foot mark was held as the undistorted dimension (zero distortion at 12). Thus, the photograph distance 7 to 12 foot mark was 22954 microns, the equivalent tape distance was 5.000 feet, the distance from the wall to the forward lens node was 14.19 feet and so the calibrated principal distance is 65.14 millimeters. The distortion curves (Figure 12) result when 65.14 millimeters are used to compute the 7 to 8, 7 to 9. 7 to 11, and 7 to 13, which are subtracted from the corresponding normalized mean distances. Data for the average radial distortion curve is given in Table II and graphed in Figure 13.

The tendency toward wide angle lenses for underwater use requires that the test tank or swimming pool be large enough to accommodate the lens field of view. For example, at a 14 foot object distance, the field of view for a 70mm camera with a 38mm focal length lens would be about 28 feet; at a 30 foot object distance the field of view would be about 60 feet. Thus, for underwater surveying cameras which may be intended for missions where the object distance will be 30 feet, the size of the calibration range must be commensurate with this distance.

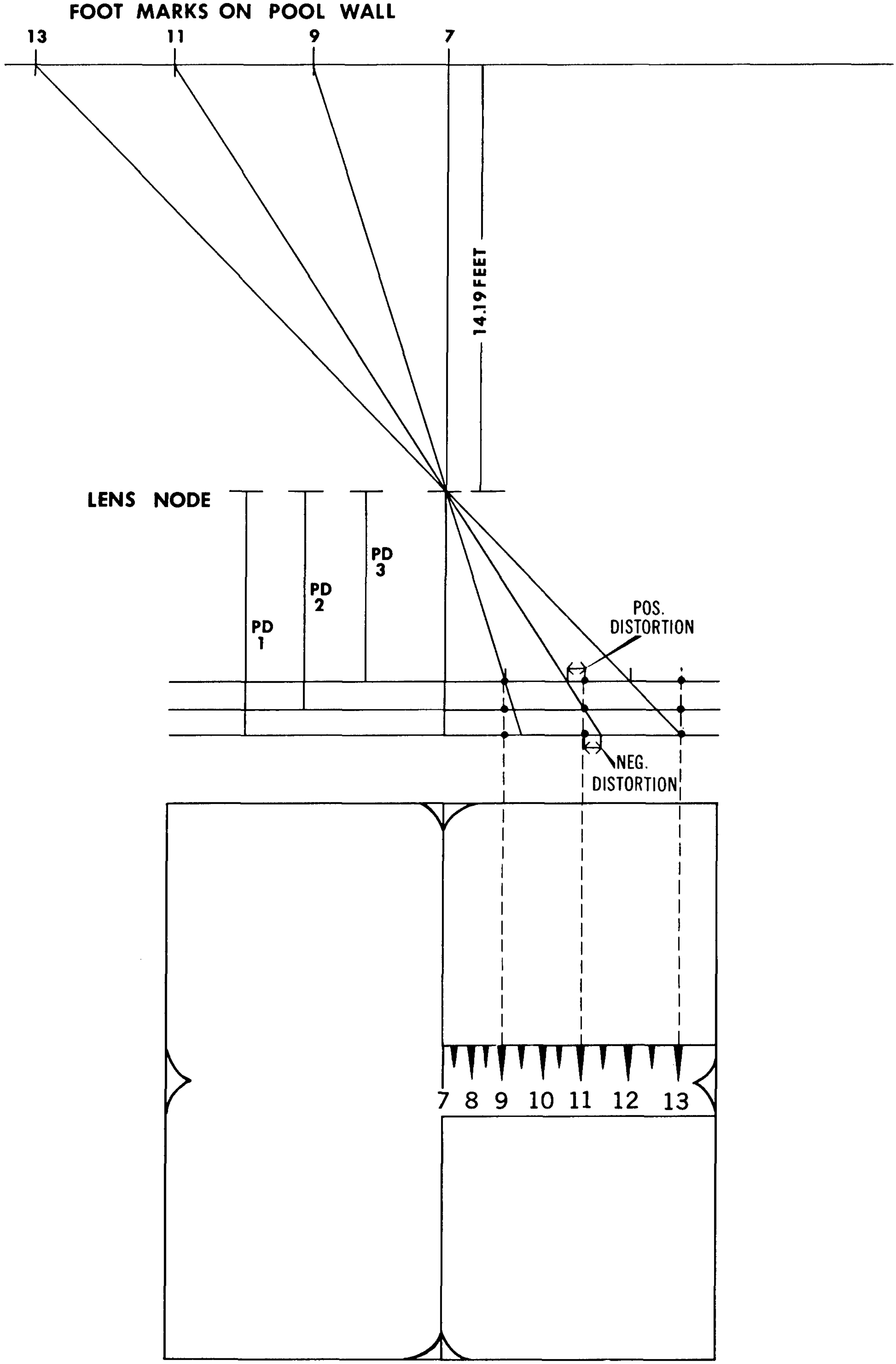


FIGURE 11 CALIBRATION DIAGRAM

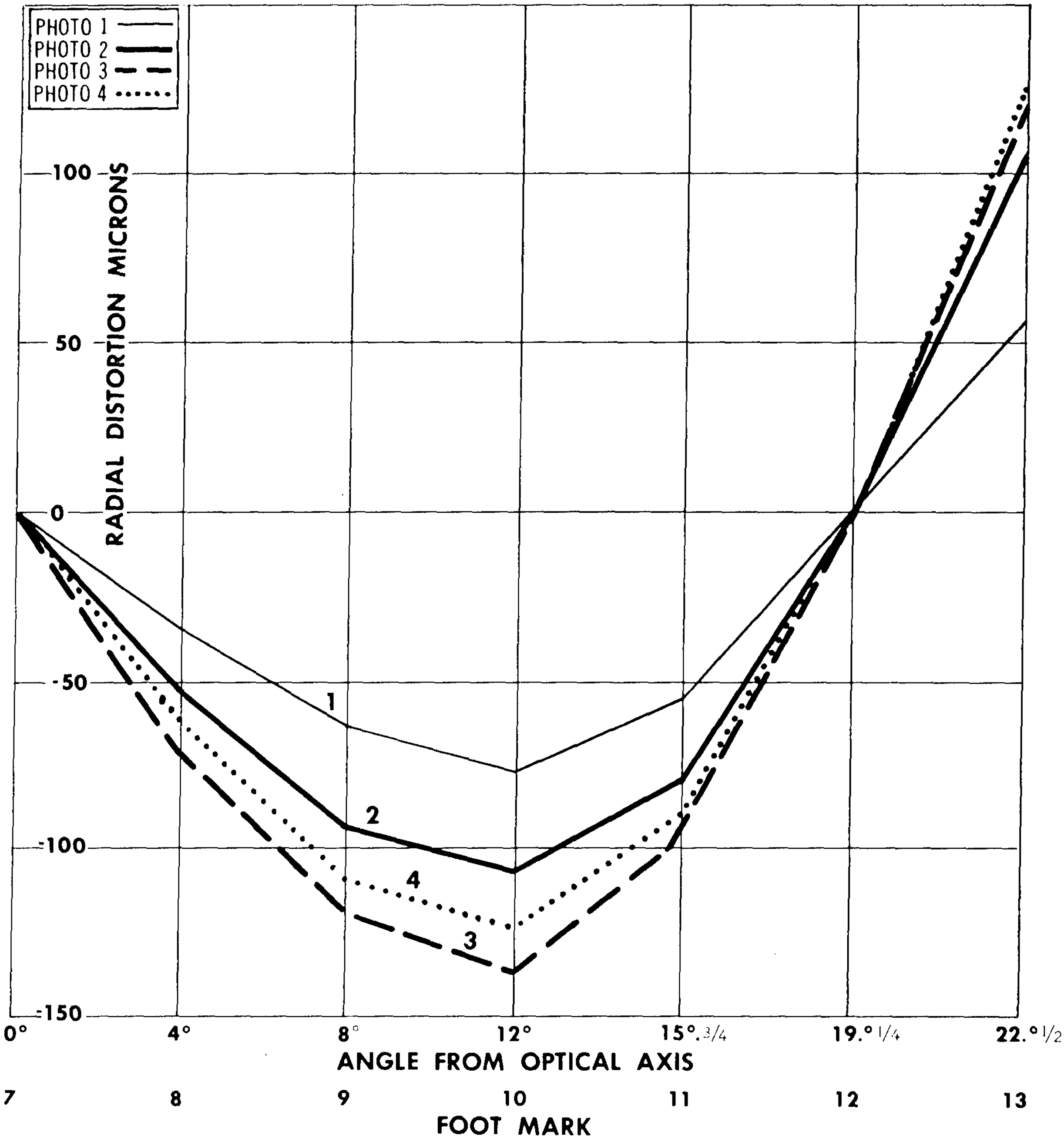


FIGURE 12 RADIAL DISTORTION CURVES

TABLE 11

DISTORTION COMPUTATION DATA

Point	Range Distance From Center	Mean Photo Distance	Computed Photo Distance PD=65.14	Radial Distortion Error	Approx. Angle From Center
	Feet	Microns	Microns	Microns	Degrees
7	0	0	0	0	0
8	1.000	4537	4591	-54	4
9	2.000	9084	9181	-97	8
10	3.000	13661	13772	-111	12
11	4.000	18282	18363	-81	15 3/4
12	5.000	22954	22954	0	19 1/4
13	6.000	27646	27544	+102	22 1/2

DISTORTION COMPARISON

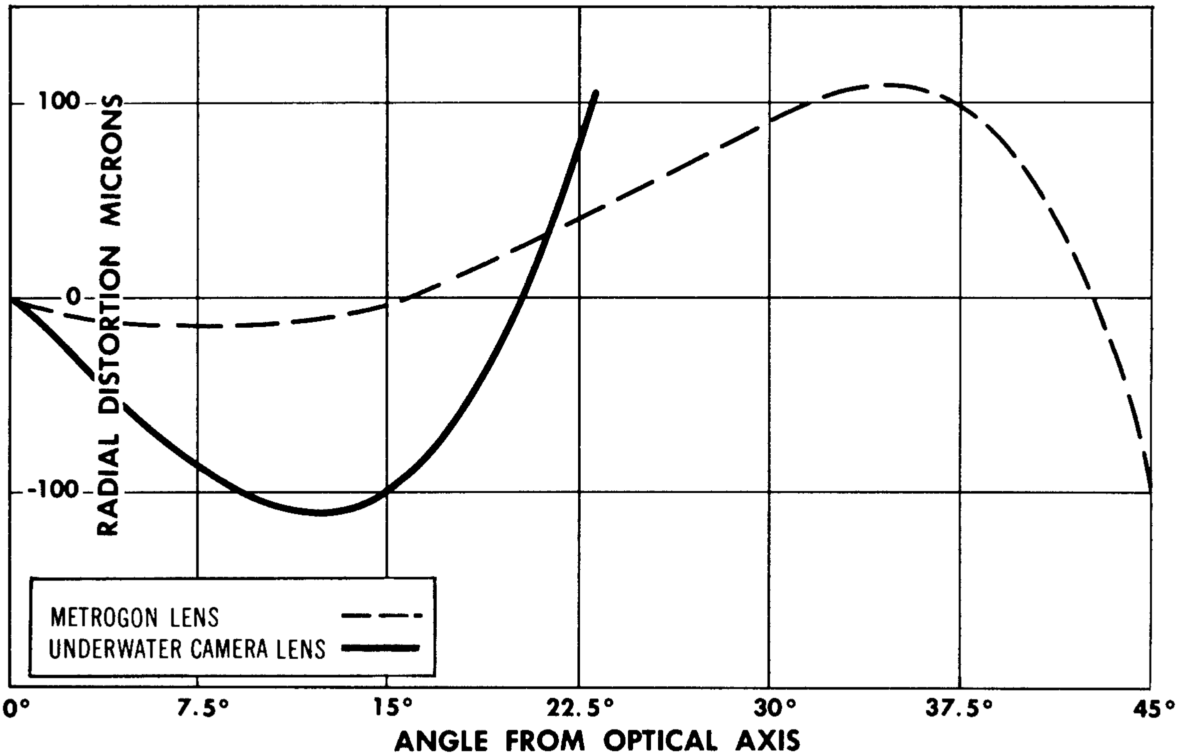


FIGURE 15

AVERAGE RADIAL DISTORTION CURVE

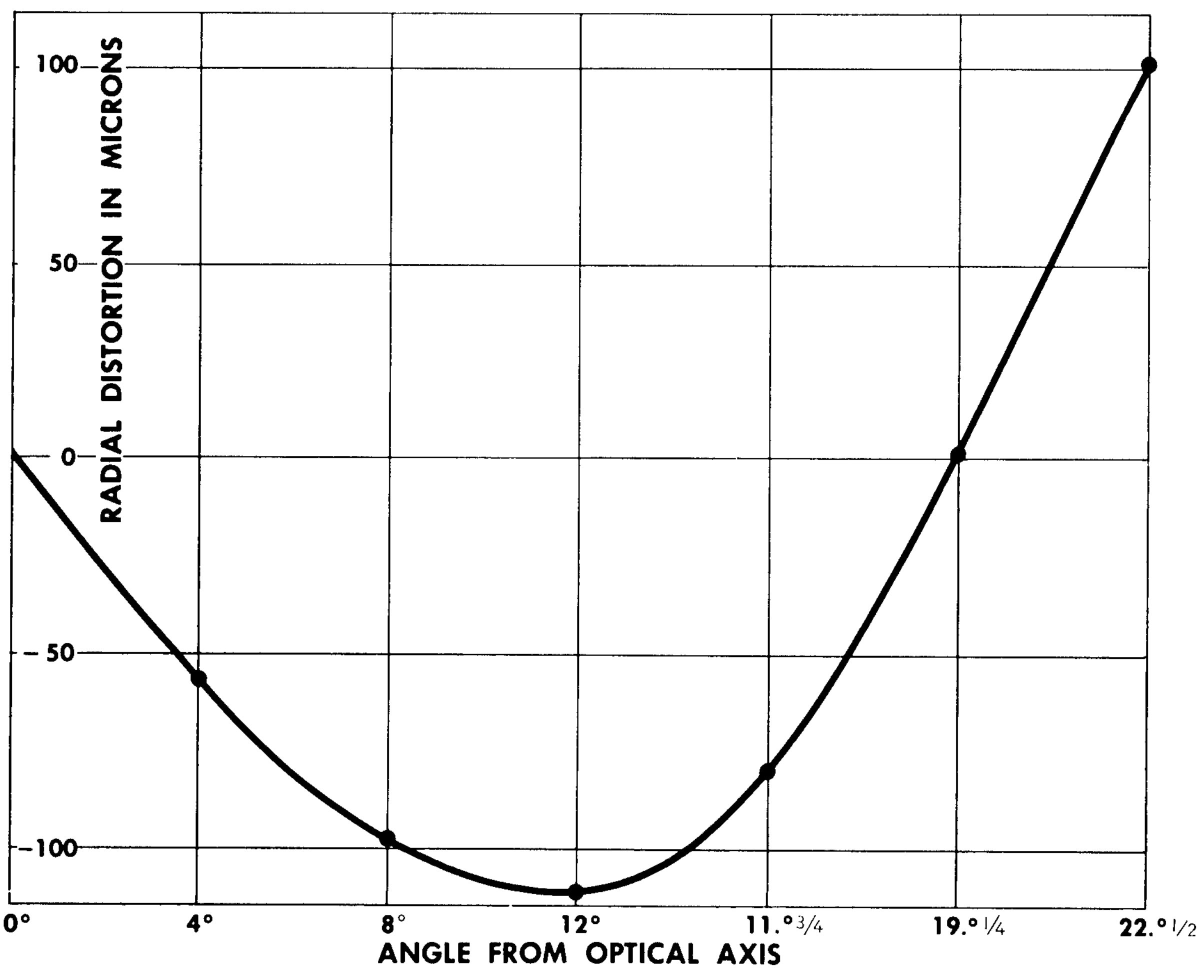


FIGURE 13

The underwater bench calibrator has no such size problem and, further, the calibration can take place in the comfort of the office (Figure 14). The bench calibrator consists of a bank of projectors set at known angles. A reticle consisting of cross hairs and resolution targets is projected through the lens to the focal plane. The images of the reticle can then be photographed or observed and the distortion, the difference between the resultant angle and the known projected angle, can then be computed. [McNiel, 1966].

NAVOCEANO has conducted underwater photogrammetric missions with two 35mm EG&G underwater cameras, Model 207A, but no lens data other than the fact that they were Hopkins-designed, water-corrected for plane parallel port, 35mm f/4.5 were provided by the manufacturer. An underwater bench calibrator was used to calibrate these cameras at the Naval Photographic Center[1]. The results of this calibration are presented in Tables III and IV. Note, however, that the distortion values are based on zero distortion at 7 1/2 degrees, which results in all negative values. The negative curvature, however, is due to lens design.

Calibration problems were caused by the fact that underwater cameras are not yet designed for photogrammetry or easy calibration. The small focal planes, the inability to view the focal plane directly, ill-designed or lack of fiducial marks, forward pressure ports that are not fixed to the lens system, and inefficient film flattening devices all contribute to accuracy and precision errors.

The magnitude of the distortion error as found by both the field test range and the bench calibrator proved to be within tolerable range. A comparison of the Rebikoff-modified Shipek radial distortion curve with a typical aerial cartographic camera metrogon lens shows that both lenses produce a total error of about 200 microns (Figure 15). However, the shape of the curves are different, with the aerial camera distributing the error over a 9 inch format while the underwater camera distributes this error over a 70mm (2.75 inch) format. Thus, a better comparison is made when the underwater camera's exposures are enlarged such that the principal distance of these cameras are equivalent to the focal length of the metrogon lenses (152.5mm). A comparison of the equivalent of the radial distortions is given in Table V.

TABLE V

EQUIVALENT RADIAL DISTORTION COMPARISON

Lens	Focal length-P.D. (millimeters)	Enlargement Ratio	Distortion (microns)	Equivalent Distortion (microns)
metrogon	152.5	1	210	210
Rebikoff-Shipek	65.14	$\frac{152.5}{65.14}$	212	496
EG&G	45.5	$\frac{152.5}{45.5}$	280	938

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1 NAVOCEANO Contract No. 62306-68-M-1388, Photogrammetry Inc.

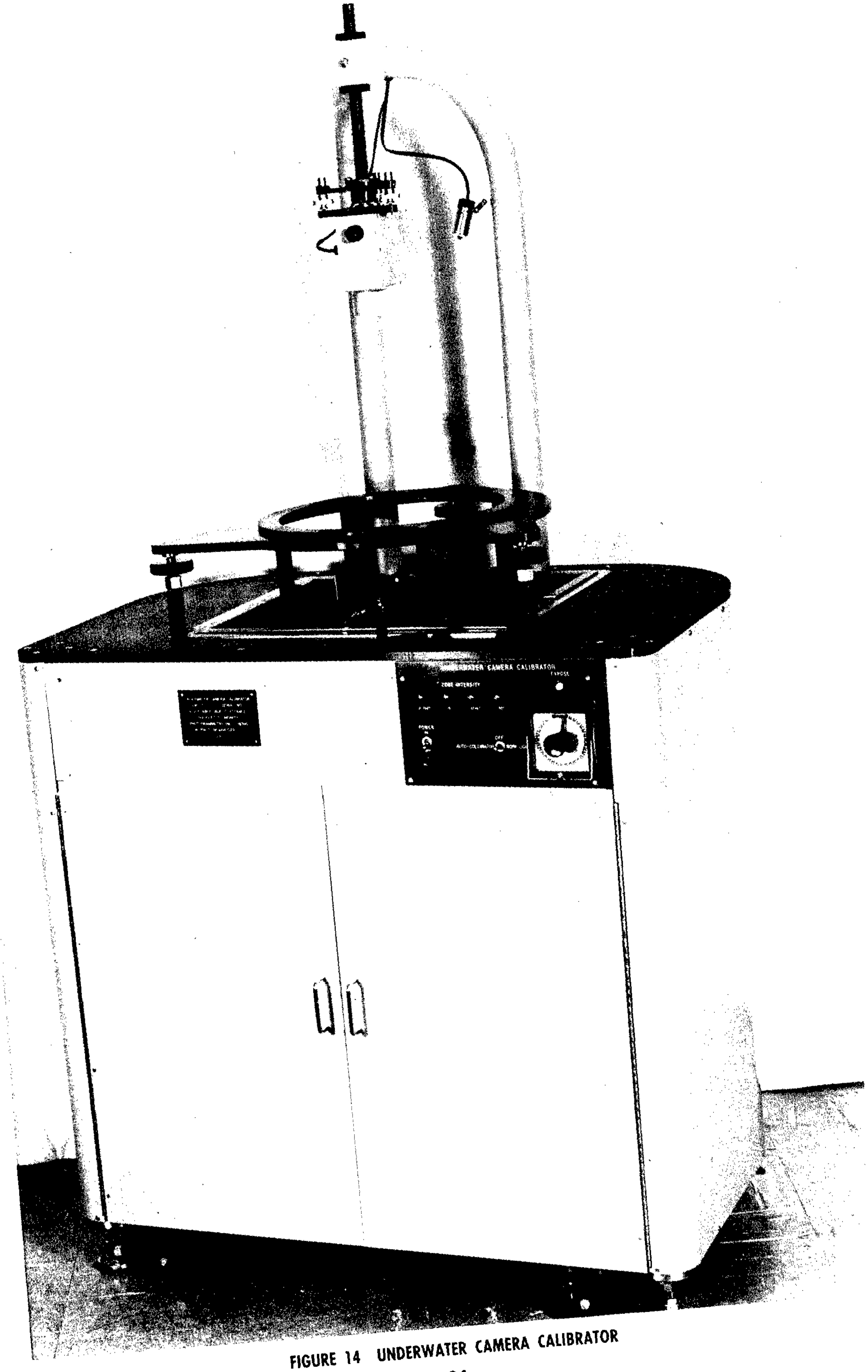


FIGURE 14 UNDERWATER CAMERA CALIBRATOR

TABLE III

EG&G Model 207A Underwater Camera, Serial No. 5

Resolving Power - Lines per Millimeter

Tri-X-Film

Distance (ft.)		0°	7.5°	15°	22.5°
∞	R	47	46	47	35
	T	47	46	31	29
50	R	47	47	42	
	T	45	45	31	
30	R	45	46	40	
	T	45	45	31	
20	R	50	46	43	
	T	50	44	37	
15	R	54	46	39	43
	T	48	48	34	26

649GH Spectrographic Film

Distance (ft.)		0°	7.5°	15°	22.5°
∞	R	295	235	150	68
	T	295	235	90	62
50	R	237	218	145	
	T	224	222	122	
30	R	265	233	145	
	T	265	219	145	
20	R	240	195	121	
	T	240	220	107	
15	R	255	205	130	87
	T	255	205	110	33

Metrical Data

Nodal Object Distance (ft)	Nodal Image Distance (mm)	Principal Point (mm) ap_x	cp_y	Distortion (mm) 15°	22.5°
∞	45.6	18.1	-0.7	-0.06	
50	45.8	18.0	-0.9	-0.06	
30	45.8	18.1	-0.6	-0.06	
20	46.0	18.1	-0.6	-0.06	
15	46.1	17.9	-0.8	-0.06	
	45.6			-0.06	-0.28
15	46.1			-0.06	-0.28

Fiducial Distance, ab= 35.91 mm

TABLE IV

EG&G Model 207A Underwater Camera, Serial No. 6

Rosolving Power - Lines per Millimeter

Tri-X-Film

Distance (ft)		0°	7.5°	15°
∞	R	48	42	45
	T	48	45	36
50	R	46	41	40
	T	46	40	35
30	R	48	41	40
	T	51	40	34
20	R	48	41	41
	T	48	43	36
15	R	51	40	35
	T	51	40	36

649GH Spectrographic Film

Distance (ft.)		0°	7.5°	15°
∞	R	275	193	127
	T	275	145	86
50	R	265	208	104
	T	265	165	93
30	R	340	165	127
	T	340	130	79
20	R	305	204	155
	T	305	180	134
15	R	244	208	118
	T	244	212	115

Metrical Data

Nodal Object Distance (ft.)	Nodal Image Distance (mm)	Principal Point (mm) ap_x	cp_y	Distortion (mm) 15°
∞	45.3	18.5	-1.0	-0.08
50	45.5	18.4	-0.9	-0.08
30	45.5	18.3	-1.2	-0.08
20	45.7	18.5	-1.0	-0.08
15	45.8	18.4	-1.1	-0.08

Fiducial Distance, ab = 35.94mm

Radial distortion with magnitudes as large as these are usually no problem to photogrammetrists. The problem occurs when these photographs are used with existing optical-mechanical photogrammetric equipment. These instruments employ aspheric plates or mechanical correctors to remove lens-class distortion, but no such plates or correctors are available for underwater cameras (nor could there be until these distortions were calibrated). Consequently, when these underwater photographs, uncompensated for distortion, are used in existing photogrammetric equipment, the resulting three dimensional models were found to be warped (distorted).

The final selection of the 70mm Rebikoff-modified Shipek camera was based on its trade-off advantages. While this camera had no film flattening device, a slow two or three second recycle time, and no intervalometer, it did have the advantage of a large format and little distortion. On the other hand, an uncorrected Hydro Products 70mm camera has three to four times greater radial distortion (Figure 16).

Exterior Orientation - The function of exterior orientation is to permit the reconstruction of the attitude and position of each exposure station in the object space coordinate system. Exterior orientation is sometimes conducted in two phases, relative and absolute orientation. Relative orientation relates the attitude (pitch, roll, and yaw) of one camera station to its conjugate station. This orientation exists when the bundle of rays from one photograph intersects with the bundle of rays from its overlapping neighbor. In so doing, a three dimensional model is created and an x, y, z model coordinate system is established.

The function of absolute orientation is to transform the arbitrary model coordinate system to the object space coordinate system X, Y, and Z. In effect, the model is brought to the correct location, leveled and pointed in the correct direction, and changed to the correct scale (in matrix form, translation, rotation, and stretch).

To facilitate exterior orientation the solution was performed in two dimensions (radial line plot) with relative and absolute orientation accomplished simultaneously. This technique yields a horizontal solution independent of the vertical solution and is widely used to establish additional horizontal control data. These data are required for the compilation of planimetric maps (horizontal information only), photomosaics, or additional control for three dimensional plotting. This method is reliable if the mission photography has less than 5 degrees pitch and roll and the elevation variation is less than 10 percent of the flying height.

The radial line plot takes advantage of the correct horizontal angular relationship which exists on near-vertical photographs. Since all perspective distortions and lens distortions radiate from the center of a vertical photograph, a straight line from the center to any pair of selected images will subtend a correct horizontal angle. Hence, each photograph can be treated as a plane table station and therefore selected image points may be positioned by triangulation[1] of the rays (Figure 17). This was done with the 380 photographs which covered the 160 foot square control network. The work was made easier by enlarging the photographs to a 9 inch by 9 inch format and by a machine which makes a representative cardboard template for each photograph by cutting a precise slot for each selected ray (Figure 18). The entire assembly was

[1] Absolute and relative orientation accomplished by resection and intersection.

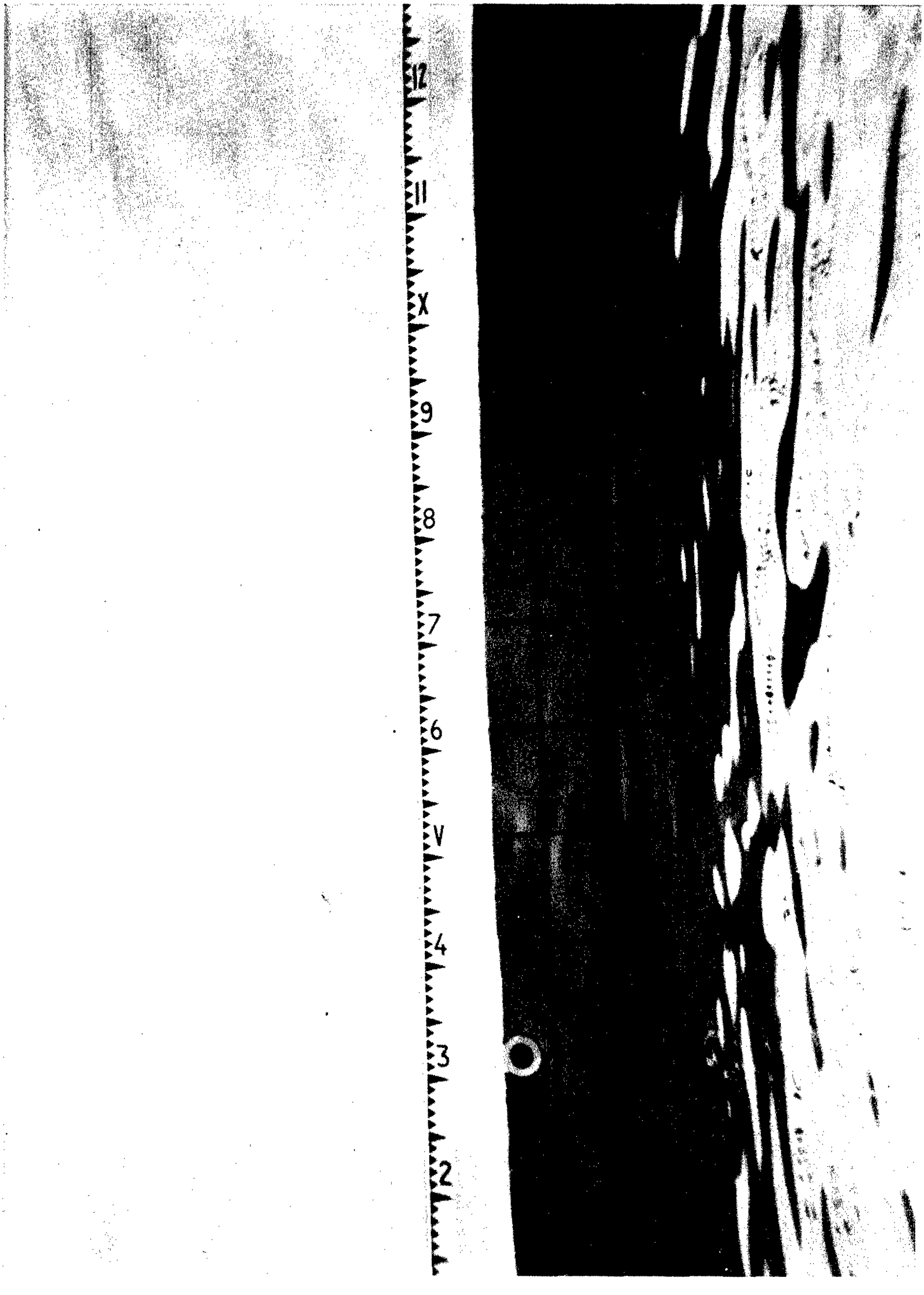


FIGURE 16 UNDERWATER PHOTOGRAPH—UNCORRECTED LENS SYSTEM

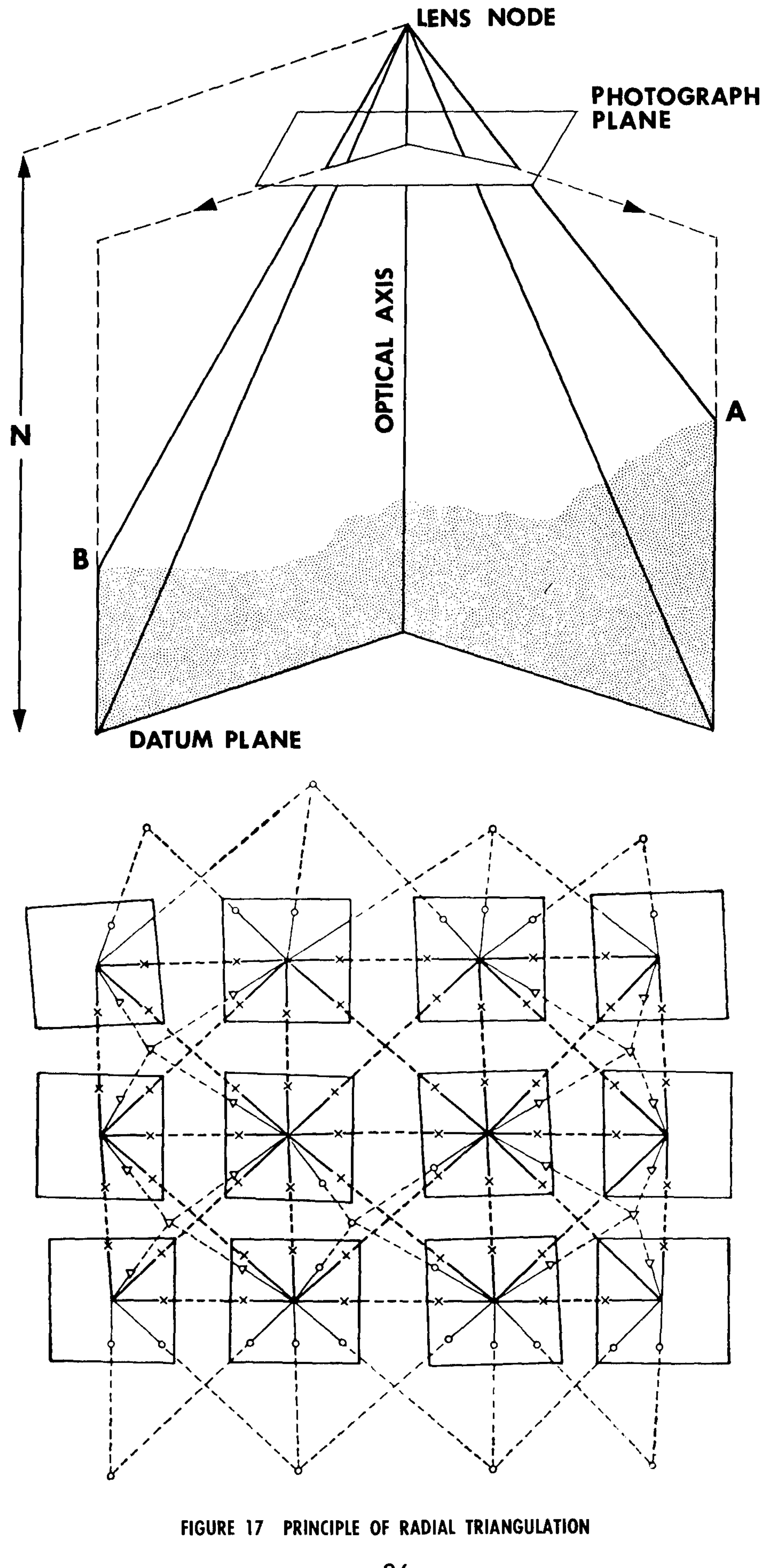


FIGURE 17 PRINCIPLE OF RADIAL TRIANGULATION

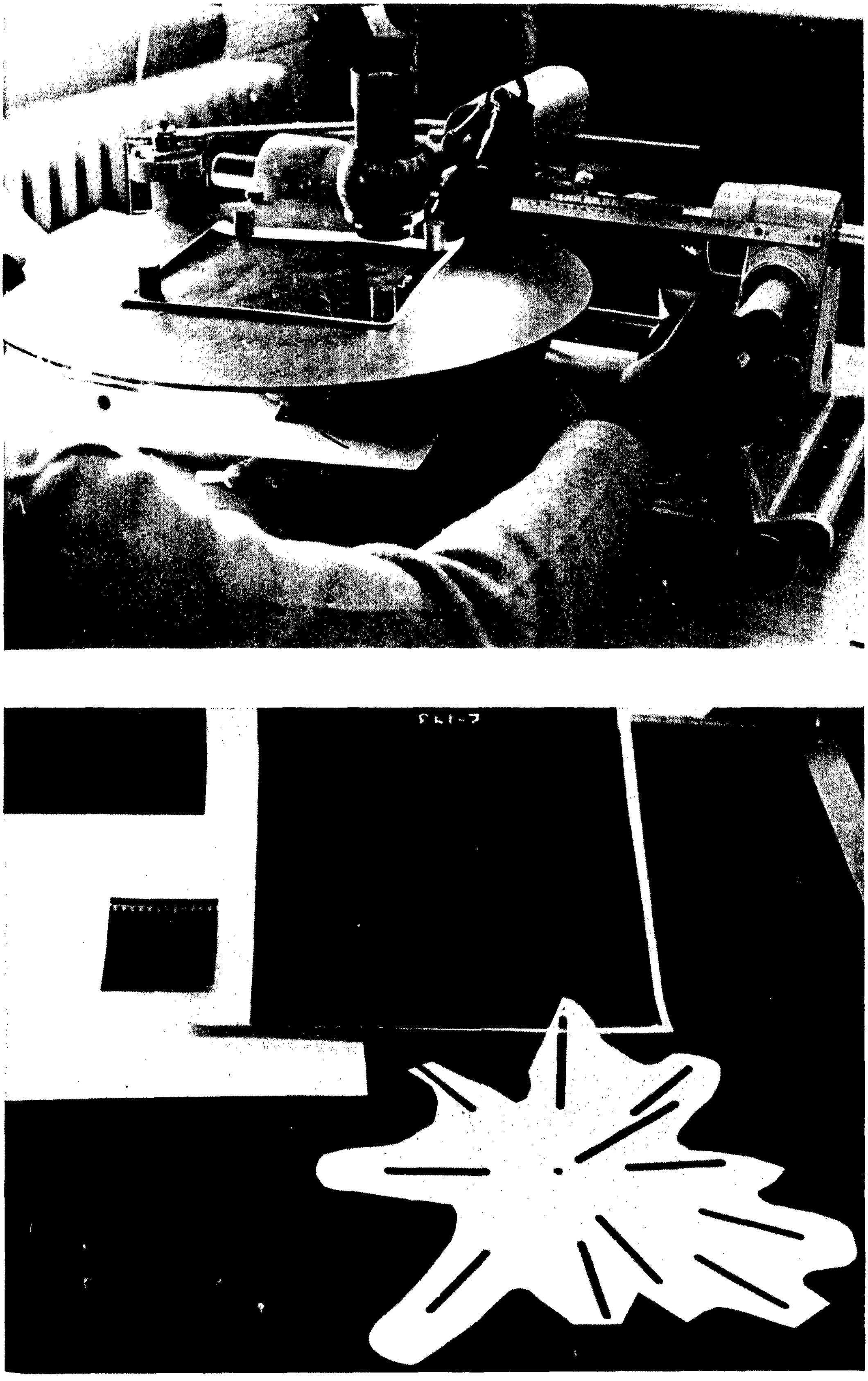


FIGURE 18 SLOTTED TEMPLATE CUTTER AND FINISHED TEMPLATE

interlocked by small metal studs which were free to slide to the intersection position. The only fixed points which were not allowed to adjust were the four corners of the control network. Thus, at least 9 points were established for each photograph, totaling approximately 1200 additional horizontal control points (Figure 19). These points were used to draw a planimetric map.

An examination of the supplemental control was made by comparing the photogrammetric location of the 32 plastic markers with the expected ground position of the markers. It was found that the root mean square error of the horizontal photogrammetric solution throughout the area was 1.2 feet (probable error 0.8 feet). This error was probably equal to the actual ground control accuracy of the markers.

COMPILATION AND FINAL PRESENTATION

Compilation is the technique of transforming the three dimensional or two dimensional models into meaning by the selection of image detail. This may vary from simply tracing details from a photograph, to a complete orthographic representation of the three dimensional model (a relief map). In an order of increasing complexity the methods are: single photo tracing, radial line intersection, parallax meter, spatial parallax, optical spatial reconstruction, and analytic digital transformation. The optical spatial method was used to compile a relief map for the photography of the test area. This method encompasses a whole realm of optical and optical-mechanical machines. For this test the multiplex projection equipment was used (Figure 20). This machinery produces a complete horizontal and vertical solution. An approximate interior orientation was achieved by enlarging the photographs to the proper ratio of metrogon focal length to underwater lens principal distance as in Table V. A contact film positive was made which was in turn used to make a glass diapositive in the standard multiplex printer. The disadvantages of this technique are the added cost of making the diapositive, the degradation of detail, and the erroneous lens compensation of the multiplex printer.

As usual, a relative orientation was empirically achieved by the removal of y-parallax. An absolute orientation was arrived at by orienting the models to the supplemental control established by the radial line plot - 7 horizontal position image points. The models were leveled to an arbitrary datum 32 feet below sea level (state of tide unmeasured). This allowed all contours to have positive value.

Even with this approximate interior orientation it was possible not only to draw contours with a one inch contour interval and discern differences in elevation to 0.3 inch, but also bridge three models (carry forth the level from one model to the next) (Figure 21). Only three models were compiled owing to the high cost of compilation - about eight hours per model were required. The rest of the area was compiled as a planimetric map with each coral head shown by form lines which show the shape and indicate the height of the heads (Figures 22, 23).

A photo mosaic of the entire area is presently in process. This mosaic will be a fully controlled mosaic in which each photograph is rectified to the supplementary control established by the radial line plot. In rectification and photograph tilt is removed and it is brought to common scale. The controlled mosaic can then by treated as anorthographic map since all gross distortions are removed.

OCEAN BOTTOM MAPPING

Mapping at great ocean depths is more difficult by far than mapping in

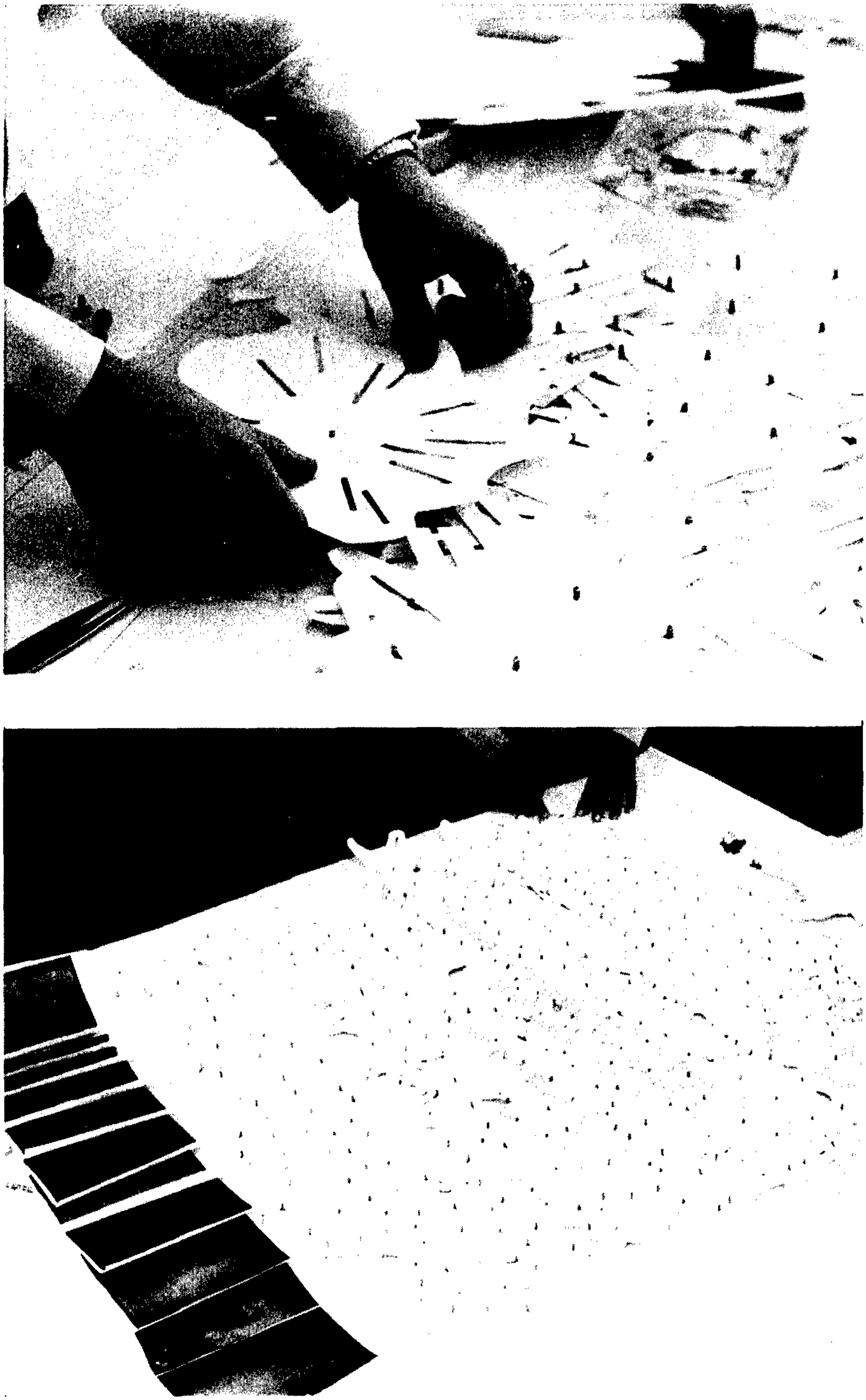


FIGURE 19 SLOTTED TEMPLATE ASSEMBLY

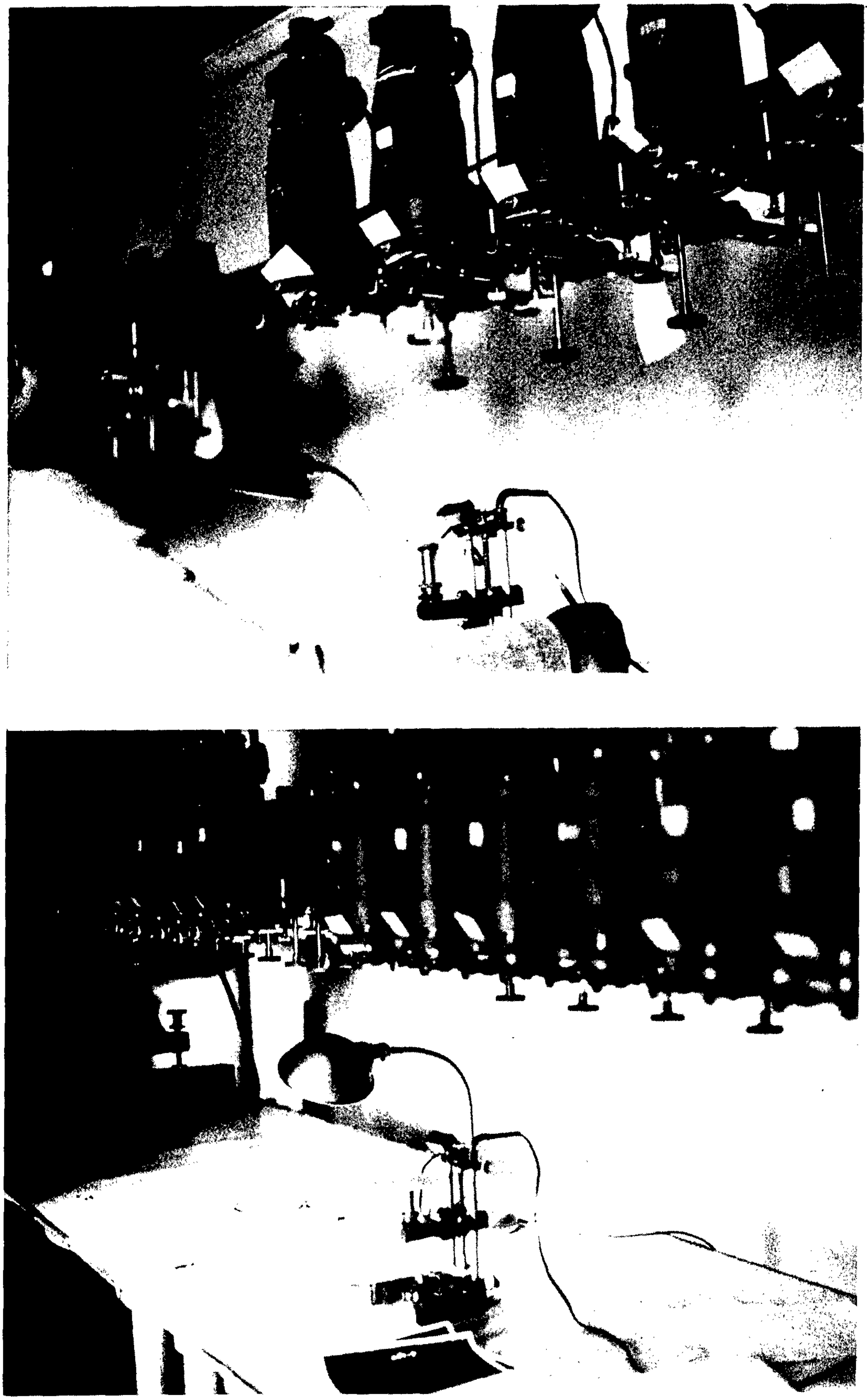


FIGURE 20 MULTIPLEX PROJECTION SYSTEM

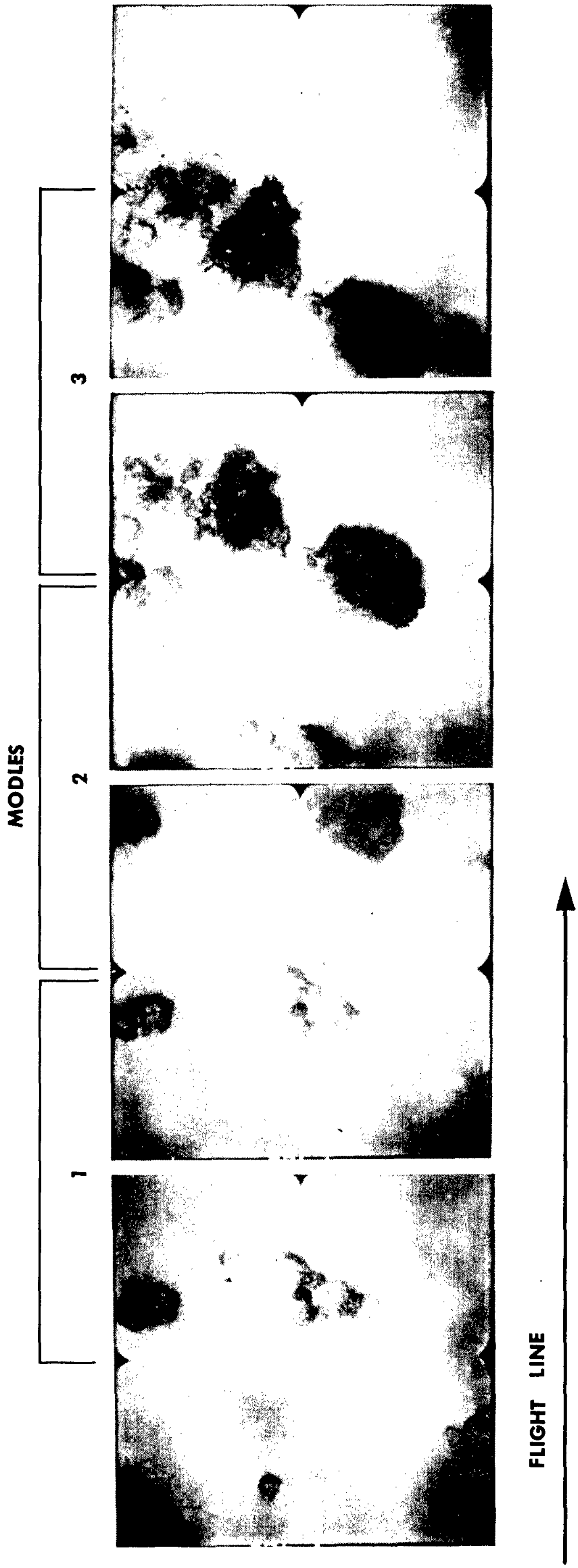
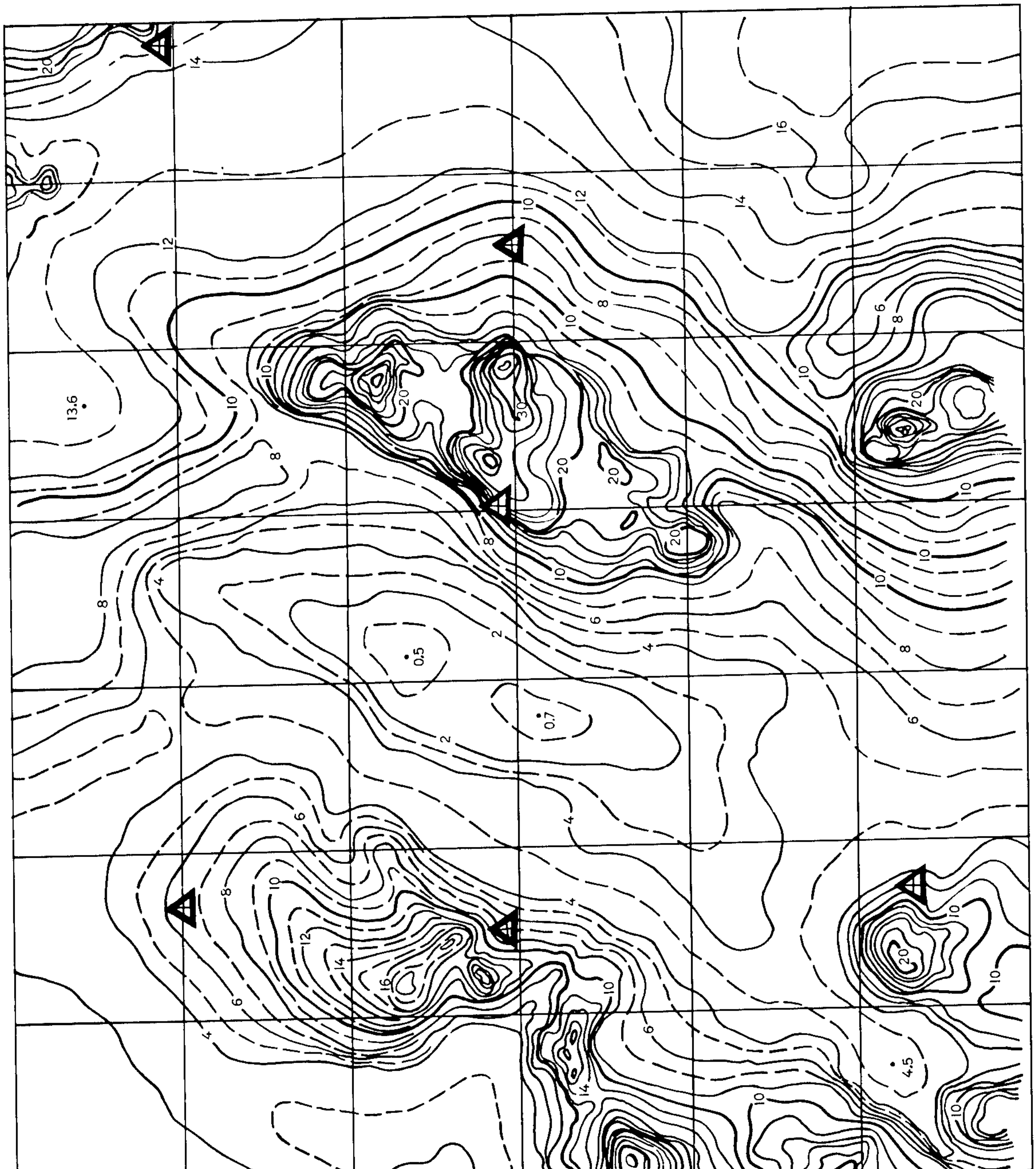


FIGURE 21 COMPILATION PHOTOS—THREE MODELS



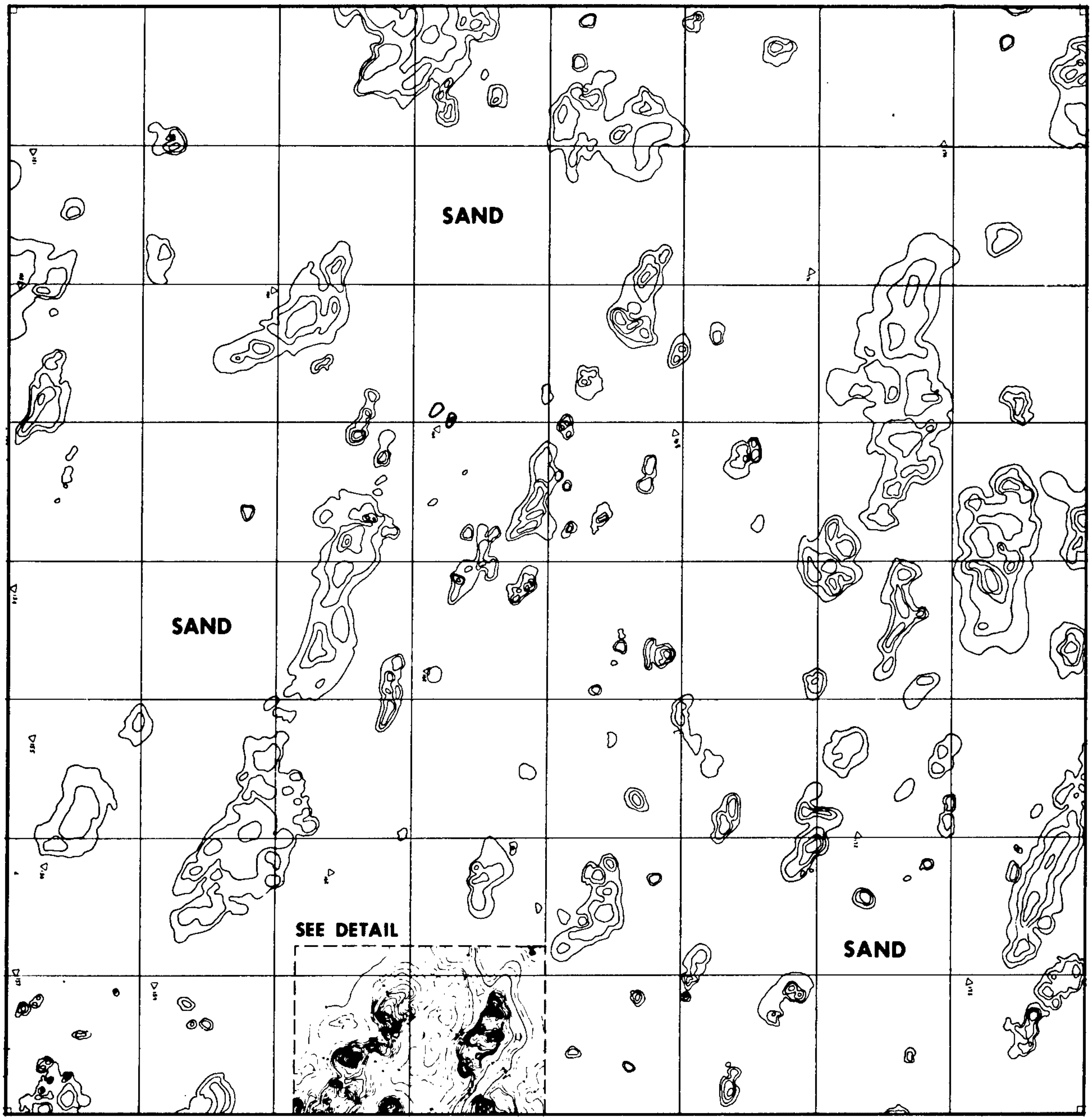
9'

GRID INTERVAL 4.5'
CONTOUR INTERVAL 2 INCHES (1 INCH SUPPLEMENT)

UNDERWATER TOPOGRAPHIC MAP
(REFERENCE LEVEL 32 FEET BELOW SEA LEVEL)

FIGURE 22

PHOTO COMPILATION



GRID 20 FOOT INTERVAL

160 FEET

FORM LINES INDICATE LOCATION AND SHAPE OF CORAL HEADS

FIGURE 23 PLANIMETRIC MAP OF THE AREA

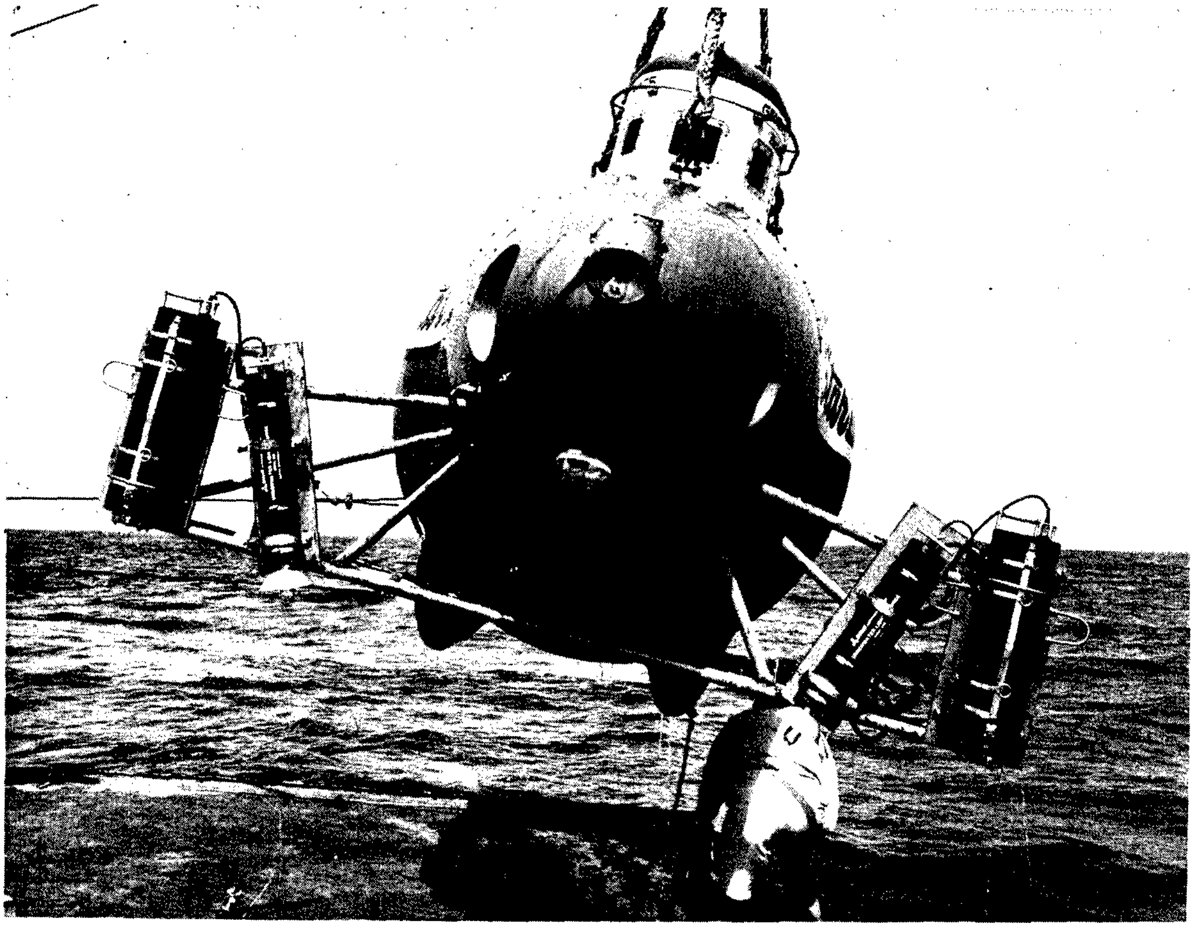
ambient light. It was found that ambient light photography was possible at up to 600 feet [Busby 1967]. But in the deep ocean, illumination must be provided for piloting and photographing the area; positioning and navigation devices must be used to obtain ground control, special cameras must be employed to withstand the pressure and hold sufficient film, and great care must be taken to fly straight and level. Even so, experiments with the manned submersibles STAR III and ALUMINAUT have demonstrated that it is possible to map the ocean bottom [Pollio, 1968].

A practical deep ocean photogrammetric light source was found to be the EG&G, 250 watt-second, electronic flash. This strobe was found to provide more than enough light for normal angle photography at 30 to 50 feet above the bottom. The strobe was usually placed so that the light angle to the field of view was about 10 to 15 degrees which was a compromise between the best position to retard back scatter and the best position to uniformly illuminate the field. But this arrangement also produced shadows which hindered the photogrammetric solution. The shadows not only concealed details needed for contouring, but they were cast in different directions which made the stereo pair seem dissimilar.

Relative ground positions could be obtained photogrammetrically from a physical base line or a grid as previously described but this would be tedious and could also be dangerous owing to submersible entanglement. The best method should employ a bottom positioning system which provides not only ground positions for the photogrammetric solution but also the real-time data required to fly the coverage pattern. Tests to date show that this technique can be developed [Merrifield, 1968; Spiess, et al, 1966].

Recently, tests were conducted with STAR III where neither a physical base line nor a transponder system was available. This method employed a twin camera system which in effect established a base at each camera station. Two EG&G Model 207A underwater cameras were mounted parallel with an 8.89 foot base (Figure 24). This arrangement not only increased the area coverage but also gave a partial orientation solution. At each exposure station the altitude, and therefore the scale of the photograph, could be computed by the image parallax in the side lap area. In Figure 25 the known data is the fixed base (B=8.89 feet) and the camera principal distance, (PD = 45.5mm). The measured data is the parallax to common images in the side lap area. A photo coordinate system is established for each side lap pair, as in the diagram, and the y coordinate is read for each common image. The parallax is defined as the difference of y coordinates, $p = y-y'$. Suppose a common image in the side lap area measured $y = 13.42$mm on the right photo and $y = -13.54$mm on the left, then the parallax of that image is 26.96mm. By the formula given in Figure 25 the relative height of the camera base is 15.0 feet above that point. Similar computation of other points in the side lap area will yield the attitude of the cameras; hence, the vehicle with respect to the bottom. Thus, if the vehicle's pitch and roll are known, the slope of the photographed area can be computed.

Inspection of this computation shows that the reliability of the height solution is directly a function of the principal distance. The principal distance, once calibrated, must not change under the varying stress conditions of the ocean depth. This requires a sturdy camera construction in which the lens system is not altered by pressure. No reported tests have been made which could determine the principal distance variation under stress. Likewise, no known tests have been made to inspect the variation of the principal distance due to the change in the index of refraction owing to the change in the density of sea water.



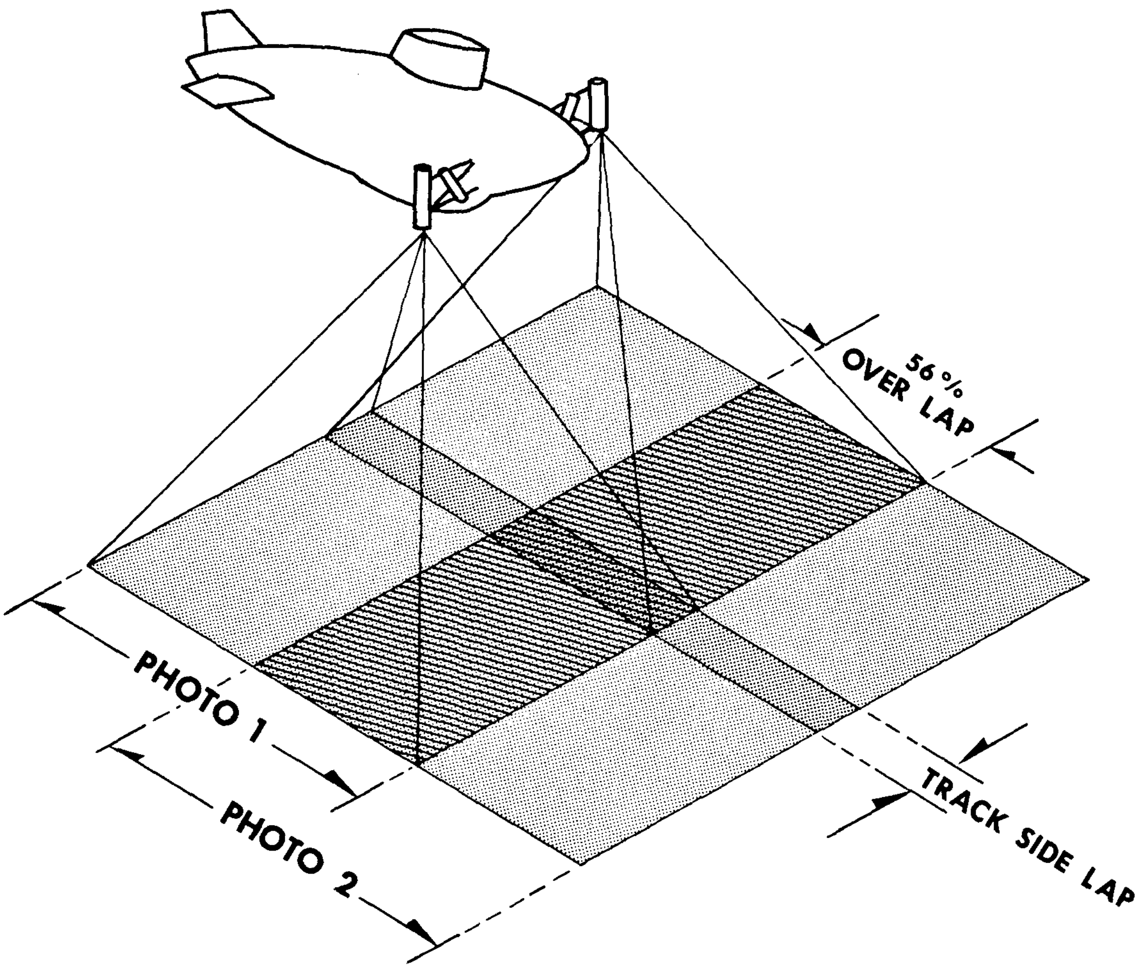
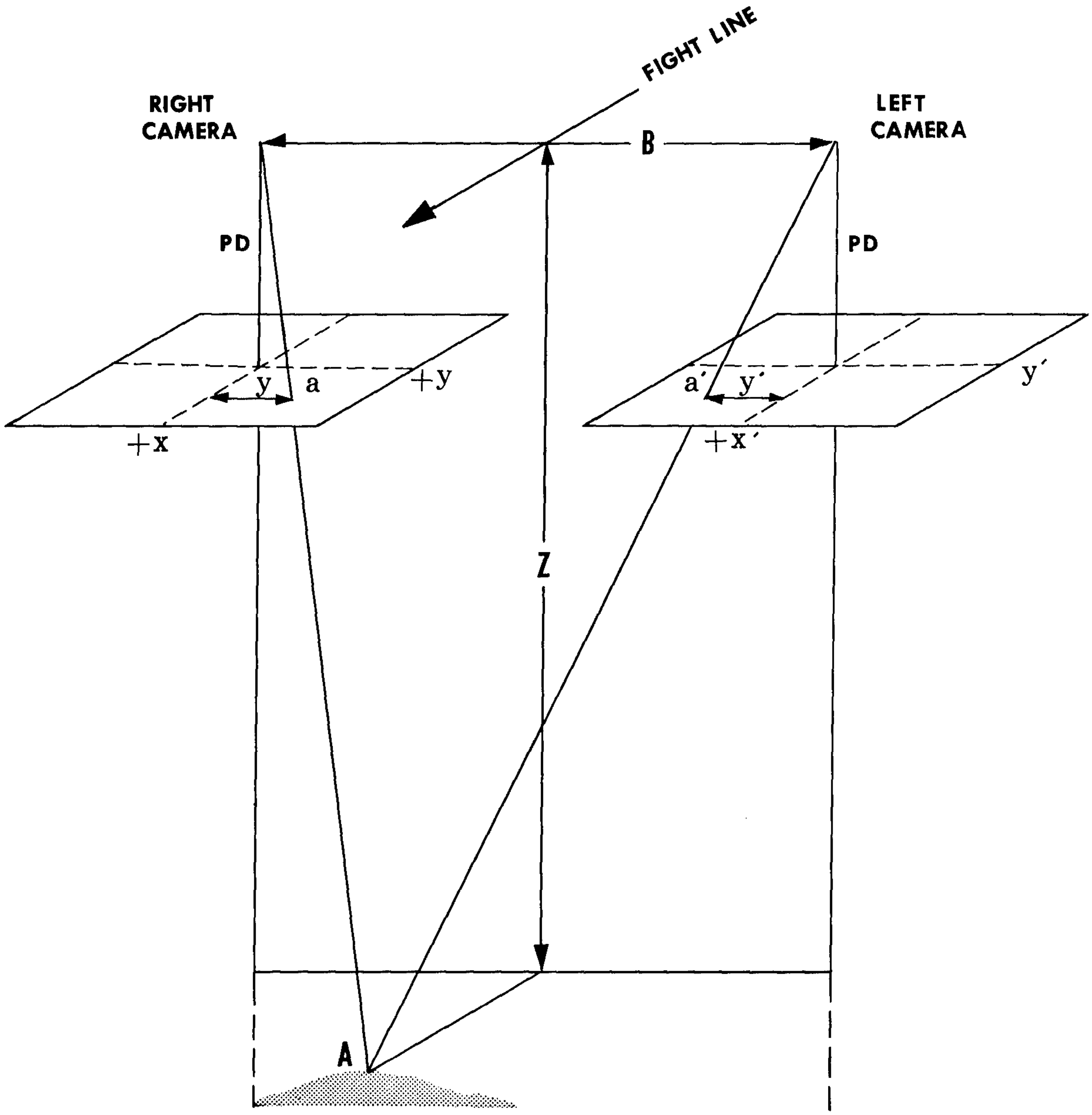


FIGURE 24 STAR III WITH CAMERA AND STROBES



B = CAMERA BASE, THE DISTANCE BETWEEN OPTICAL AXES

PD = PRINCIPAL DISTANCE (CALIBRATED)

A = DETAIL IMAGE POINT IDENTIFIABLE ON RIGHT AND LEFT PHOTOGRAPH (a and a')

y = MEASURED y COORDINATE OF IMMAGE a

y'= MEASURED y COORDINATE OF IMAGE POINT a'

p = PARALLAX = y - y'

Z = ALTITUDE OF THE CAMERA BASE ABOVE POINT "A" RELATIVE TO THE PLANE OF THE PHOTOGRAPH

$$Z = \frac{B}{p} PD$$

FIGURE 25 Z COORDINATE FROM PARALLAX MEASUREMENT

The problems presented by non-photogrammetric cameras are tolerable but all is lost if the vehicle cannot maneuver sufficiently to maintain altitude and attitude. In areas of rough bottom where the variations in the bottom are of the same magnitude as the flying height, photogrammetric solutions become impossible. These areas fall out of the realm of photogrammetry and other methods must be found to map these bottom areas [Pruna and Mairs, 1968].

But in February 1968, tests were conducted with ALUMINAUT in areas of marginal relief (10 to 15 feet). Inspection of this film reveaied continuous overlapping stereo photography interrupted occassionally by strobe misfire. At times the overlap ceased when the vehicle passed over submarine canyons and revines with vertical walls.

It was found, however, that long strips of this photography could be aligned and positioned by the numerous position fixes obtained from the surface tracking vessel. As with STAR III, a twin camera system with a fixed base was used on ALUMINAUT which allowed a scale and attitude orientation for each exposure. As a result this photography will be processed into strip maps and mosaics.

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13. ABSTRACT

The reliability of a photogrammetric system is a function of the degree of constraints applied to the system. Mapping tests have been performed to investigate the relative importance of these constraints. Underwater mapping consists of five elements: (1) ground control, (2) photogrammetric equipment, (3) field techniques, (4) photogrammetric analyses, and (5) final presentation.

Ground control was provided by a 160 foot square underwater net. A photogrammetric camera was improvised by calibrating a hand-held 70mm water corrected underwater camera, which was mounted to the wet submersible PEGASUS. Photogrammetric analyses were performed by assembling a radial line plot for a horizontal control solution and employing this horizontal control for a vertical bridge of three models. The result was an establishment of over 1200 additional horizontal points, a planimetric map of the entire area, a detailed, one inch, contoured map of the three models, and a photo-mosaic of the area.

Tests with the submersibles STAR III and ALUMINAUT have shown that contoured strip maps can be made with parallel mounted cameras. This arrangement allows for the computations of the camera height and gives some indication of the bottom attitude. This additional information along with ground coordinates at each exposure station provides sufficient data to compile a map.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
WATER CORRECTED LENSES						
UNDERWATER LENS CALIBRATION						
UNDERWATER CONTROL NETWORK						
WET SUBMERSIBLE						
UNDERWATER PHOTOGRAPHY						
BOTTOM TOPOGRAPHY						
PHOTOGRAPHY FROM SUBMERSIBLES						
BOTTOM MAPPING						
MAPPING FROM MANNED SUBMERSIBLES						